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SYMPOSIUM 1
SEDIMENT YIELD AND SOURCES

EROSION POTENTIAL OF SOILS

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ABSTRACT

Erosion and sediment from farmland remains a serious problem in the United States. Gaining national concern is the erosion and sediment resulting from urban development.

Predicting the erosion potential of soils is one of the first steps used by the Soil Conservation Service in planning conservation systems that control soil erosion on farmland and urban developments alike.

This paper describes the application of research to produce a practical field procedure for determining the erosion potential of soils. Special emphasis is given to the soil factors that influence erosion and to how soil surveys are used to predict the areas of potential erosion.

INTRODUCTION

With the growing concern about producing enough food for ourselves and our world neighbors, erosion control is more important now than ever before. Farmers in the United States have responded to better prices and reduced acreage controls to bring more land into production. They have increased planting acreage an estimated 5 percent in 1975, putting more land into crops than they have in 18 years (Grant, 1974). In all parts of the country there are farmers who are ignoring the lessons of history--not to mention data contained in soil surveys--and who are planting crops where it is difficult to protect the soil from washing or blowing. The potential increase in production resulting from the increased acreage of cropland could be offset to a large extent by the loss of future productive capacity of the soil caused by wind and water erosion.

Average crop yields have tended to increase in the United States even though soil losses are often excessive. Modern technology, including heavy use of fertilizer, is largely responsible. But this is a short-term effect. In the long run, erosion decreases the yield potential and increases production costs (Schaller, 1975).

One fact emerges clearly from our experience in striving for higher production--the need is more urgent than ever to increase conservation on America's farms and ranches before even more damage is done to our agricultural resource base.

Erosion is also occurring in the nation's urban areas, contributing sediment to streams. Construction sites are highly susceptible to erosion. Large housing developments and major construction projects may keep an area bare and vulnerable for 1 to 3 years. The period of greatest erosion hazard on individual home sites usually lasts 3 to 12 months. Many local communities, counties, and states, are concerned about the urban and sediment problem. A number of states have enacted erosion and sediment control laws in order to protect the environment from degradation: Hawaii, Iowa, Maryland, Michigan, Montana, North and South Carolina, Ohio, Pennsylvania, and Virginia. The Virgin Islands have also enacted erosion control legislation. Nearly half of these laws include farmland.

SCS, over the last 40 years has helped land managers by supplying the basic resource information, such as soil surveys, and the land and treatment alternatives from a conservation and economic viewpoint. A major tool in planning land use alternatives and conservation treatment is the soil loss equation. This equation, based on nearly 60 years of erosion research in the United States has evolved into a practical procedure for determining the amount of erosion expected on specific soils when they are treated in specific ways.

HISTORY OF SOIL LOSS EQUATIONS

Erosion research in the United States began in 1917 when M. F. Miller organized, at the Missouri Agricultural Experiment Station, the first plot study of the effect of crops and crop rotations on runoff and erosion (Duley and Miller, 1923). Others soon followed Professor Miller's lead and, by 1933, 10 federal-state experiment stations were doing research on the nation's most critically eroding soils. By 1943 the basic factors affecting runoff and soil loss were established and the early studies were discontinued.

A number of additional studies were made that led to the development of equations for calculating field soil loss. Zingg (1940) published an equation relating length and percent of slope to relative soil loss. Using this equation, Smith (1941) added crops and conservation practice factors and the limiting annual soil loss concept in development of a method for applying conservation practices to soils of the Midwest. A nationwide workshop was held in Cincinnati during the summer of 1946 under the direction of Musgrave. This group reviewed all soil loss data in the U.S. to 1946, reevaluated factors previously used, and added a rainfall factor.

The resulting formula, generally known as the "Musgrave equation," was widely used for estimating sheet erosion from watersheds in flood abatement programs.

An improved soil loss equation developed in the late 1950's overcame many of the limitations of earlier equations (Wischmeier and Smith, 1965). The new developments freed the equation from some of the generalizations and geographic and climatic restrictions of earlier models. The equation became known as the "Universal Soil Loss Equation." Research is continuing on the equation and the supporting data. Emphasis is being placed on the rainfall characteristics and soil erodibility factors in the states west of the Rocky Mountains. The use of the equation to predict soil loss from construction sites is also being explored.

The research shows that the amount of erosion is highly dependent on the following factors: the characteristics of the rainfall; the ability of the soil to absorb rainfall and its susceptibility to detachment and transport; the slope length and gradient; and the amount and kind of ground cover. Herein lies the means of erosion control. Man can influence the ground cover by using certain cropping systems and management practices. He can influence the slope length by contour cultivation or building terraces to intercept water. He can influence to some degree a soil's ability to absorb water and its susceptibility to detachment and transport. The erosion equation gives a measure of these factors so that the amount of erosion can be predicted under any combination of land use and management. Such predictions furnish a sound basis for making shifts in land use and selecting the right combination of conservation practices.

THE SOIL LOSS EQUATION

The soil loss equation reflects the influences of all the major factors known to influence rainfall erosion. The equation:

$$A = RKLSCP \dots\dots\dots (1)$$

where: A is the computed soil loss (sheet-and-rill erosion) in tons;
R, the rainfall factor, is the number of erosion-index units in a normal year's rain;
K, the soil erodibility factor is the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow on a 9-percent slope 72.6 feet long;
L, the slope length factor, is the ratio of soil loss from the field slope length to that from a length of 72.6 feet on the same soil and gradient;
S, the slope gradient factor, is the ratio of soil loss from the field gradient to that from a 9-percent slope;
C, the cropping management factor, is the ratio of soil loss from a field with specified cropping and management to that from the fallow condition from which the factor K was evaluated;
P, the erosion control practice factor, is the ratio of soil loss with contouring, stripcropping, or contour-irrigated furrows to that with straight row farming up and down slope.

Values can be determined for each of these factors and the equation solved to determine the amount of soil loss for specified management systems.

The soil itself is one of the most important of the erosion factors. The susceptibility of different kinds of soil to erosion under cultivation varies widely.

The balance of this paper deals with the soil as a factor in the erosion equation, discussions of those soil properties that influence erodibility, a description of how erodibility of soil is measured and estimated, and the use of soil surveys in determining the erosion potential of soils.

SOIL ERODIBILITY FACTOR K

The soil erodibility factor K is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. It is a value determined experimentally for selected benchmark soils and is estimated for other soils based on their soil properties.

The measurements of K factors are made with a rainfall simulator. The original plots were 72.6 feet long and had a 9-percent slope. On soils

not having this slope the K factors are converted to the standard 9-percent slope. The measurements are made on soil kept in continuous cultivated fallow. When all these conditions are met, each of the factors L, S, C, and P have a value of 1.0 and K equals A/R.

Direct measurements of K values range from as low as 0.02 on certain tropical soils in Puerto Rico and Hawaii to .69 on certain Corn Belt soils (Wischmeier, 1971).

From a large number of experiments, the important soil characteristics that influence the erodibility of soil have been identified. (Wischmeier and Mannering, 1969; Barnett and Rogers, 1966, Roth et al, 1974). No single soil property proved capable of predicting the soil's resistance to erosion by rainfall and runoff. Indeed, there are many variables and the interactions among them are highly complex. The significant variables are soil texture (particle-size distribution), soil organic matter content, soil structure (aggregate size, shape, and durability), and the permeability of the soil profile.

Soil texture

Generally speaking, soils that are high in silt, low in clay, and low in organic matter are the most erodible. The soil particles are easily detached and the pores are easily plugged, which creates more runoff and erosion. A soil is less erodible with less silt content regardless of whether the increase is in clay or sand. The very fine sand fraction behaves like silt--that is, the addition of the very fine sand fraction to the silt fraction improves the prediction of erodibility.

When clay content increases and other factors are held constant, erodibility decreases. Most of this effect is due to increased cohesiveness. A parameter has been discovered that does an adequate job of expressing the effect of particle size on erodibility. It is the product of percent silt plus very fine sand and percent sand plus silt. This parameter accounted for 85 percent of the variance observed in K values for 55 rainfall-simulator-tested soils (Wischmeier et al., 1971).

However, percentages of silt, sand, and clay must be considered in relation to other physical and chemical properties. As organic matter increases and silt is held constant, erodibility decreases. When clay content is high, the effect of organic matter or sand/silt ratio on erodibility diminishes.

This relationship does not adequately predict the erodibility of high clay subsoils when they are scalped (Roth et al., 1974). Roth attributed greater stability to amounts of iron and aluminum hydrous oxides. However, among the soils studied, the soils with the highest amount of iron contain the highest amount of clay; therefore a relationship still exists between high clay content and stability.

Coarse fragments of stone and rock in the soil reduce the erosion rate by protecting the finer particles from raindrop impact and washing. The effectiveness in erosion resistance is a function of the percentage of the area covered by the coarse fragments. The greater the percentage covered by stones, the less the soil loss (Meyers et al., 1972).

Soil organic matter

Soil organic matter influences the erodibility of the soil probably because of its binding effect on holding soil particles together. Soils high in organic matter resist dispersion and the transporting forces of rainfall and runoff. They also have higher infiltration rate, faster permeability, and higher water-holding capacity than similar soils with low organic matter. Soils that are scalped show this relationship clearly by their greater susceptibility to erosion.

A number of studies concluded that in a range of organic matter from 0 to 4 percent (a) soil erodibility tends to decrease appreciably as organic matter increases and (b) the magnitude of organic matter effect is related to texture. That is, when clay content is high, the effect of organic matter on erodibility is low; when clay content is low, the effect of organic matter on erodibility is high. Organic matter exceeding 4 percent seems to have little additional effect on erodibility (Wischmeier and Mannering, 1969; Yamamoto and Anderson, 1973).

Soil structure

Soil structure, refers to the way soil particles are held together in aggregates. The size, shape and durability, of soil structure are important variables that influence erodibility of the soil. Soil structure grade or durability is described as weak, medium, or strong, depending on how firmly the soil particles resist rupture when squeezed between thumb and finger. Erodibility is inversely related to structural durability--erosion is highest on the weakest structure and lowest on the strongest structure. One of the reasons certain tropical soils are so resistant to erosion is their especially strong structure. The aggregates are little affected by raindrops. The size and durability of aggregates also affects the infiltration rate. Durable granular aggregates have fast infiltration. Soils with weak aggregation tend to seal quickly when raindrops break down the aggregates, causing slow water infiltration rate.

Soil permeability

Soil permeability is the ease with which water passes through the whole soil profile. It influences erosion by its effect on runoff. The effect is not evident on storms of short duration (2 hours or less) but on storms of long duration the effect is strongly apparent. The most erosive soils are those with permeable upper layers and slowly permeable

lower layers. The upper layers become saturated quickly and additional rain runs off causing the soil to flow with it, even on gentle slopes. Yet highly permeable soils, even very clayey ones having non-swelling inactive clay may have little erosion under cultivation, even on strong slopes. If the soil is permeable enough to accept the rain as it falls, then no runoff occurs and erosion is no problem.

THE SOIL ERODIBILITY NOMOGRAPH

The research that has been carried on through the years by SCS and then ARS has produced measured K factors on a number of soils. Furthermore, it has furnished the data for the relationships between a large number of soil properties that affect erodibility. From this data a nomograph has been constructed so that K factors can be estimated for a wide variety of soils if certain soil characteristics are known (Wischmeier, 1971).

Soil scientists in SCS have established K factors for most soils in the United States using either measured data or the nomograph to make estimates. These factors are in SCS technical guides and other SCS reports and publications.

USING SOIL SURVEY TO PREDICT SOIL LOSS

Much of the information required for solving or applying the erosion equation can be obtained from the soil survey. The kind of soil is determined from the soil survey. K factors for the soils are obtained from a list in the published soil survey or in SCS technical guides by named kinds of soils. The slope length (L) and slope gradient (S) can be estimated from the soil survey. The slope gradient is described in the soil mapping unit or in the name of the mapping unit, e.g., Cecil sandy loam, 5- to 8-percent slopes. The length (L) may be described in the mapping unit or can be estimated by interpretation of the soil map. It is estimated by determining the distance from the ridge to the foot of the slope or a well defined channel in a representative number of mapping units.

The rainfall factor (R) for a survey area is known. It is a part of the SCS field office technical guide. It can also be read off of an "R" factor map such as that found in SCS Technical Release No. 51 (Rev.), Jan. 1975.

If these factors are multiplied the product, RKLS, is the estimate of the erosion potential index. It is equivalent to the amount of annual erosion that would occur on a bare soil cultivated up and down slope with no conservation practices.

The erosion potential index (RKLS) by itself is a useful concept. It shows the areas that are most likely to erode if cultivated. If the area is cultivated, the erosion potential index shows the relative erosion hazard of the area.

Multiplying this erosion potential index by appropriate values of factors C and P reduces it for effects of cropping system, cultural management, and supporting control practices, so that the complete equation predicts average annual soil loss (A) for a specific cropland situation.

If the C factors for the existing cropping and cultural management system and the P factor for the existing supporting practices are used, then the amount of soil loss (A) can be estimated for the existing situation.

If the amount of soil loss (A) is unacceptably high, the soil loss equation can be solved for C and P to find out which set of conservation cropping systems and supporting practices are needed to bring the soil losses down to an acceptable level.

The Soil Conservation Service uses this approach to help land managers plan and carry out a conservation program. The equation is solved so that soil loss is equal to or less than the maximum rate of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely. This is called soil loss tolerance (T). It is the amount of soil we can afford to lose because soil formation about keeps pace with this rate of loss.

Soil loss tolerance varies according to kind of soil. It ranges from 1 to 5 tons per acre per year depending on depth of rooting zone and the amount of yield reduction caused by removal of the surface layer by erosion. Each soil is carefully evaluated to determine its soil loss tolerance using the following criteria:

1. Maintenance of an adequate rooting depth for crop production. For soils that are shallow over hard rock, it is important to maintain the remaining soil; therefore, not much soil loss is tolerated. The soil loss tolerance should be less on such soils than for soils of similar depth overlaying soft substrata that can be renewed by management practices.
2. Crop yield reduction. Soils that have significant yield reductions when the surface layers are removed are given lower soil loss tolerances.
3. Maintenance of water-control structures such as open ditches, ponds, and other structures affected by sediment.

4. Prevention of gullies so that the fields can be worked efficiently by large machinery.

T factors are listed for each kind of soil in the SCS technical guides.

The soil loss equation is also used to estimate sheet and rill erosion from watersheds. The actual amount of sediment that reaches a stream is only a fraction of the soil eroded from upslope. This fraction is called the sediment yield. The ratio of sediment yield to gross erosion expressed in percent is the sediment delivery ratio. The average annual sediment yield for specific areas, unless measured for a period of years, is not easily determined but gross approximations are possible. Geologists estimate the sediment yield from a watershed by multiplying the average annual tons of soil loss for the area from all sources by the sediment delivery ratio.

CONCLUSION

In these times of worldwide concern for the environment and at the same time emphasis on greater production of food and fiber, soil erosion needs to be considered for the protection of our food base as well as for pollution control.

The interaction of a number of variables directly and indirectly influences the amount of soil erosion. A universal soil loss equation based on these interactions accurately predicts soil loss for a large part of the United States. The soil loss equation used with soil surveys is useful in predicting an area's erosion potential index and the kinds of conservation treatment required to sustain crop production economically and indefinitely, and it serves as a basis for predicting potential sediment yield.

Soil surveys are completed for about 55 percent of the United States mainly in the highly agricultural areas. A list of published soil surveys can be obtained from the Soil Conservation Service, Washington, D.C. 20250. Individual soil surveys and factors used in the soil loss equation can be obtained from the local SCS field office or the state office.

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EFFECT OF LAND USE ON SEDIMENT DELIVERY RATIOS

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ABSTRACT

Data from two subwatersheds in the Pigeon Roost Creek Watershed in northern Mississippi were used to compute sediment delivery ratios for each year of a 15-year period. Land use changes resulted in greatly decreasing land and gully erosion estimates in one watershed and slightly increasing estimates for the other. Computed annual sediment delivery ratios did not seem to change due to changing land use on either watershed. However, annual values of delivery ratios changed directly with annual runoff. The major effect of gully plugs and other conservation structures on sediment production was to negate the effect of 33 and 34 percent of the total estimated sheet and gully erosion on the two watersheds.

INTRODUCTION

Use of sediment delivery ratios is one of the methods used to estimate annual sediment yield from an ungaged watershed. By definition, delivery ratio is the proportion of gross erosion that appears as sediment yield at some point of interest in the watershed system (SCS National Engineering Handbook). In this paper, sediment delivery ratio is used as an indication of land use effects on sediment yield.

Data from two subwatersheds of Pigeon Roost Creek Watershed, a research watershed operated by the USDA Sedimentation Laboratory, were used for this study. Land use in the watershed changed before and during the 15-year period of record due to efforts of the Soil Conservation Service and United States Forest Service to improve the watershed, much of which had become severely eroded and gullied in the late 19th and early 20th centuries (Woodburn, 1949).

The major sediment sources in the watershed - upland erosion, gully erosion, and channel erosion - have been measured for estimating annual gross erosion values. These quantities with continuous runoff and sediment gaging allow the computation of sediment delivery ratios and a study of the influence of land use changes on the sediment delivery ratio.

WATERSHED DESCRIPTION

Pigeon Roost Creek Watershed is an area of 303 square kilometers (117 square miles) located in the western part of Marshall County in northern Mississippi. The watershed lies in the North Central Plateau region of the East Gulf Coast physiographic section of the Coastal Plain province (Asmussen, 1963). Surface features consist of broad flat flood plains

with rolling, severely eroded uplands. Elevations range from approximately 90 meters (300 feet) at the watershed outlet to 180 meters (600 feet) on the watershed divide. The watersheds used in this study, designated W-4 and W-5, are subwatersheds in the upper part of Pigeon Roost Creek Watershed.

Area soils are predominately those of two soil associations: Collins-Vicksburg-Falaya association on the flood plains and Loring-Gullied association on the ridgetops and side slopes (Soil Survey of Marshall County, Mississippi, 1972). The flood plain soils are nearly level, well-drained to somewhat poorly drained soils and the steeper land is gullied and gently sloping to moderately steep, moderately well drained soils that have a fragipan. The Collins-Vicksburg-Falaya soils are brown silt loams in the surface top 15 centimeters (six inches) with silt loam subsoils. Loring soils are about 13 centimeters (five inches) of silt loam over about 66 centimeters (26 inches) of silty clay loam with a fragipan.

The gullied land is often eroded down to sands of the Coastal Plain sediments. At these places and many other areas of severe erosion, the predominately sand-bearing Tallahatta and Kosciusko geological formations outcrop (Woodburn, 1949). Thus, almost all the channels are sand-bed streams. Many of the downstream larger channels have been dredged to remove sand and to prevent out-of-bank flows that deposit sand on the fertile flood plains.

When the watersheds were instrumented in 1956, watershed W-4 contained 809 hectares (2000 acres) and watershed W-5 contained 457 hectares (1130 acres). Relocation of the gaging station in watershed W-4 on January 1, 1965 and in watershed W-5 on October 1, 1969 reduced the drainage areas to 639 hectares (1580 acres) and 405 hectares (1000 acres), respectively.

PROCEDURES

Rainfall measurement - A network of four recording raingages provide coverage for W-4 and W-5 watersheds which are adjacent to each other. Watershed precipitation was determined by the Thiessen-weighted method. All data were digitized by break-points for computer-computation of watershed storm amounts, intensities, and energy.

Land use surveys - Detailed surveys were made of watershed land use as required for soil loss estimation by the Universal Soil Loss Equation (USLE) (Spraberry, 1969). Overlays were prepared from aerial photos to show each single land use area together with its slope, slope length, and erodibility. Estimates of these land factors were all made visually and each watershed survey of land use was made independently of previous surveys. This resulted in some variation from one survey to another in estimated watershed area distribution between land slope classes; however, the same scientist made all the surveys. Gullies were located and areas of the watersheds made noncontributing by gully plugs and detention structures were located and measured.

Channel surveys - Detailed surveys of channel cross-sections were made at 152.4-meter (500-foot) intervals and repeated at about 4-year intervals. Vertical control was carried from a datum, and horizontal control was maintained using pipe section markers. Channel volumes were computed by the average end-area method to determine volume changes throughout the period of record.

Sediment load measurements - Gaging stations were established at normal sections at the watershed outlets. Continuous stage-discharge records were maintained for runoff computations. Sediment samples were collected using hand sampling methods; for the last several years, automatic samplers were used, also. Measured sediment discharge during a storm period was based first on storm sediment samples and, if measurements were lacking, on the station's sediment rating curve. Sediment movement near the streambed, which was not measured, was computed by the Colby mean velocity method (Colby, 1957).

RESULTS

Upland erosion estimates - The USLE was used to estimate annual "sheet erosion" in each watershed.

$$A = R K L S C P \quad (1)$$

The rainfall factor, R, was computed from recording raingage records. The factor values for soil erodibility, K, slope length and steepness, LS, cropping, C, and conservation practice, P, were all estimated from the land use surveys. Because land use surveys were made at intervals greater than 1 year, values of $A/R = K L S C P$ on a unit area basis were plotted and interpolated between years of surveys to obtain annual land use values. Annual erosion was then computed by multiplying these smoothed values by annual R values computed from individual raingage records and Theissen-weighted to obtain watershed values. Likewise, acres of gullies contributing to gross erosion each year were estimated by interpolating between the areas of gullies observed at each periodic survey. The yield of sediment from gullies was estimated using a 5.08-centimeter (2-inch) gully erosion rate (Woodburn, 1949) adjusted in proportion to the annual rainfall factor to account for larger or smaller yields during years of greater or lesser rainfall amounts and intensities as represented by the EI factor. Because gully plugs and small dams made significant portions of the watersheds noncontributing for sediment production, those areas were not considered in estimates of watershed gross erosion.

Channel erosion was computed over a 15-year period, 1958 to 1972 (Bowie, 1975). Annual values were estimated by straight-line interpolation of channel volumes between surveyed values. Channel losses were further adjusted between surveys in proportion to annual runoff amounts. Using annual values of sheet, gully, and channel erosion, sediment delivery ratios were computed by

$$DR = \frac{SY}{A + GU + CH} \quad (2)$$

where DR is delivery ratio; A is sheet erosion; GU is gully erosion; CH is channel erosion; and SY is sediment yield at the watershed outlet.

DISCUSSION

Sediment yield and erosion data are given in Tables 1 and 2. These data are for the sediment-contributing area only since the delivery ratio should be unaffected by that part of the watershed above conservation structures. This is not quite true since all parts of the watershed contributed to runoff. However, runoff from the non-contributing portions of the watersheds had little effect on peak rates and a limited direct effect on total direct runoff. We assumed that the major effect of runoff from the noncontributing areas was to increase the ground water supply and, hence, induce faster runoff response.

Land use changes, 1957 to 1972, on the watersheds are shown in Figure 1. Also shown are erosion potentials based on USLE computations using an average rainfall factor for the 15-yr period. During the period of record, land use changed in both watersheds. The contributing area in W-4 was changed to less erosive covers whereas, in W-5, land area under cultivation increased. Thus, predicted erosion decreased in W-4 and increased in W-5 from 1958 to 1972. Although not easily seen in the figure, the quality of the several covers improved with time, e.g. poor pasture to good pasture, thus lowering erosion potential.

However, numerous conservation structures were constructed in the watersheds. These structures caused large parts of the watersheds to be noncontributing, thus largely eliminating 33 percent of the predicted erosion over W-4 watershed and 34 percent over W-5 watershed.

Delivery ratios were computed yearly by using gross erosion as the sum of all source contributions from the contributing area only. These values are shown in Figure 2.

The gaging station in W-4 was moved between 1964 and 1965 wateryears reducing the drainage area from 809 hectares (2000 acres) to 639 hectares (1580 acres). This resulted in two populations of delivery ratios. A regression analysis on this basis for W-4 and over the entire period for W-5 indicated that the regression coefficient was not different from zero. Thus, land use changes (shown earlier) did not have a detectable effect on the sediment delivery ratio from simple regression analysis.

Table 1.--Data from Watershed W-4 for computing delivery ratios on a water year (October 1 to September 30) and contributing area basis.

Water Year	Contributing Area ^{1/}		(1) Total Sediment Yield		(2) Sheet Erosion		(3) Gully Soil Loss		(4) Total Channel Losses		Delivery Ratio 1 ÷ (2 + 3 + 4)
	hectares	acres	MT/ha	T/a	MT/ha	T/a	MT/ha	T/a	MT/ha	T/a	
1957 ^{2/}	6532	1614	---	---	---	---	---	---	---	4/	---
1958	6555	1595	11.7	5.2	42.1	18.8	9.0	4.0	7.6	3.4	0.20
1959	6386	1578	6.9	3.1	39.7	17.7	8.3	3.7	3.4	1.5	0.14
1960	6309	1559	4.0	1.8	20.0	8.9	4.3	1.9	4.0	1.8	0.14
1961 ^{2/}	6232	1540	6.3	2.8	34.5	15.4	7.2	3.2	5.4	2.4	0.13
1962 ^{2/}	6155	1521	16.1	7.2	37.7	16.8	7.8	3.5	11.2	5.0	0.28
1963	6078	1502	3.1	1.4	25.3	11.3	5.2	2.3	0.8	0.8 ^{4/}	0.10
1964	6001	1483	14.6	6.5	34.5	15.4	7.2	3.2	1.8	0.8	0.34
1965 ^{2/}	4666	1153 ^{3/}	16.8	7.5	20.2	9.0	5.6	2.5	2.7	1.2	0.59
1966 ^{2/}	4634	1145	4.9	2.2	15.0	6.7	4.7	2.1	0.2	0.1	0.25
1967	4601	1137	7.6	3.4	23.1	10.3	7.4	3.3	0.9	0.4 ^{4/}	0.24
1968	4565	1128	8.1	3.6	17.9	8.0	6.5	2.9	1.8	0.8 ^{4/}	0.31
1969 ^{2/}	4532	1120	15.7	7.0	21.7	9.7	8.8	3.9	4.3	1.9	0.45
1970 ^{2/}	4500	1112	8.5	3.8	11.7	5.2	5.6	2.5	2.9	1.3	0.42
1971 ^{2/}	4452	1100	6.7	3.0	9.0	4.0	4.5	2.0	1.6	0.7 ^{4/}	0.45
1972 ^{2/}	4395	1086	4.7	2.1	16.1	7.2	6.3	2.8	1.1	0.5 ^{4/}	0.20

1/ Area not behind conservation structures.

2/ Years of land use surveys; values of contributing area, sheet erosion, and gully loss linearly interpolated between survey values.

3/ Total watershed area of 809 hectares (2000 acres) for 1964 and earlier, 639 hectares (1580 acres) afterwards.

4/ Years of survey, losses for other years interpolated between survey values.

Table 2.—Data from Watershed W-5 for computing delivery ratios on a water year (October 1 to September 30) and contributing area basis.

Water Year	Contributing Area ^{1/}		(1) Total Sediment Yield		(2) Sheet Erosion		(3) Gully Soil Loss		(4) Total Channel Losses		Delivery Ratio 1÷(2 + 3 + 4)
	hectares	acres	MT/ha	T/a	MT/ha	T/a	MT/ha	T/a	MT/ha	T/a	
1957 ^{2/}	379	936	---	---	---	---	---	---	---	^{4/}	---
1958	369	911	18.6	8.3	24.2	10.8	5.8	2.6	4.0	1.8	0.55
1959	359	886	15.2	6.8	25.3	11.3	6.5	2.9	2.5	1.1	0.44
1960	348	861	12.1	5.4	14.8	6.6	4.0	1.8	2.7	1.2	0.56
1961	339	837	17.7	7.9	21.6	9.6	6.3	2.8	3.6	1.6 ^{4/}	0.56
1962	329	812	26.2	11.7	29.8	13.3	9.4	4.2	5.8	2.6 ^{4/}	0.58
1963 ^{2/}	319	788	7.6	3.4	20.2	9.0	6.7	3.0	1.3	0.6 ^{4/}	0.27
1964	321	792	31.6	14.1	33.2	14.8	10.1	4.5	4.0	1.8	0.67
1965	322	796	33.0	14.7	22.0	9.8	6.1	2.7	5.2	2.3	0.99
1966	324	800	14.1	6.3	17.0	7.6	4.3	1.9	2.0	0.9 ^{4/}	0.61
1967	325	804	22.2	9.9	34.5	15.4	7.6	3.4	2.7	1.2 ^{4/}	0.50
1968	327	808	21.1	9.4	26.5	11.8	5.2	2.3	3.6	1.6 ^{4/}	0.60
1969 ^{3/}	329	812	32.7	14.6	40.1	17.9	7.2	3.2	6.9	3.1	0.60
1970 ^{2/}	287	710	23.3	10.4	20.0	8.9	5.8	2.6	5.6	2.5	0.74
1971 ^{2/}	280	692	15.7	7.0	22.2	9.9	4.9	2.0	3.1	1.4 ^{4/}	0.53
1972 ^{2/}	373	674	14.1	6.3	39.2	17.5	5.8	2.6	2.9	1.3 ^{4/}	0.29

^{1/} Area not behind conservation structures.

^{2/} Years of land use survey-values of contributing area, sheet erosion, and gully loss linearly interpolated between survey values.

^{3/} Total watershed area changed from 457 hectares (1130 acres) to 405 hectares (1000 acres) on October 1, 1969.

^{4/} Years of survey of all or part of channel-losses for other years interpolated between survey values.

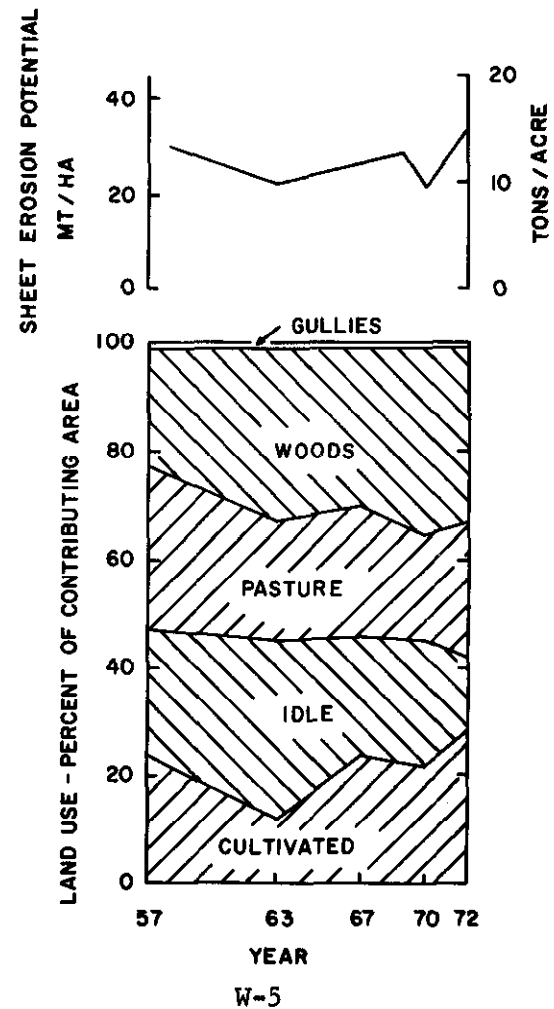
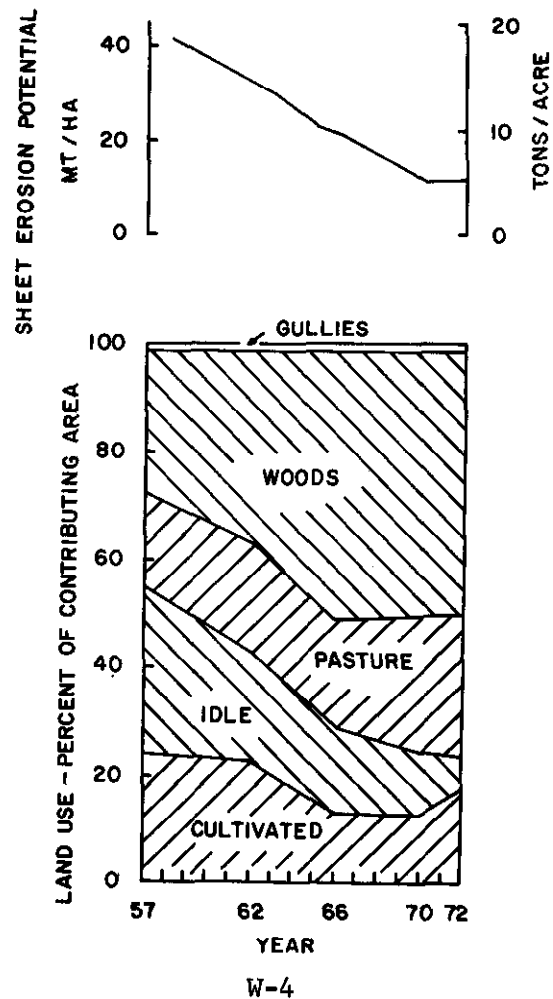


Figure 1. Land use area and quality for watersheds W-4 and W-5. Sheet erosion potential computed using average rainfall factor, R, for 1958 to 1972.

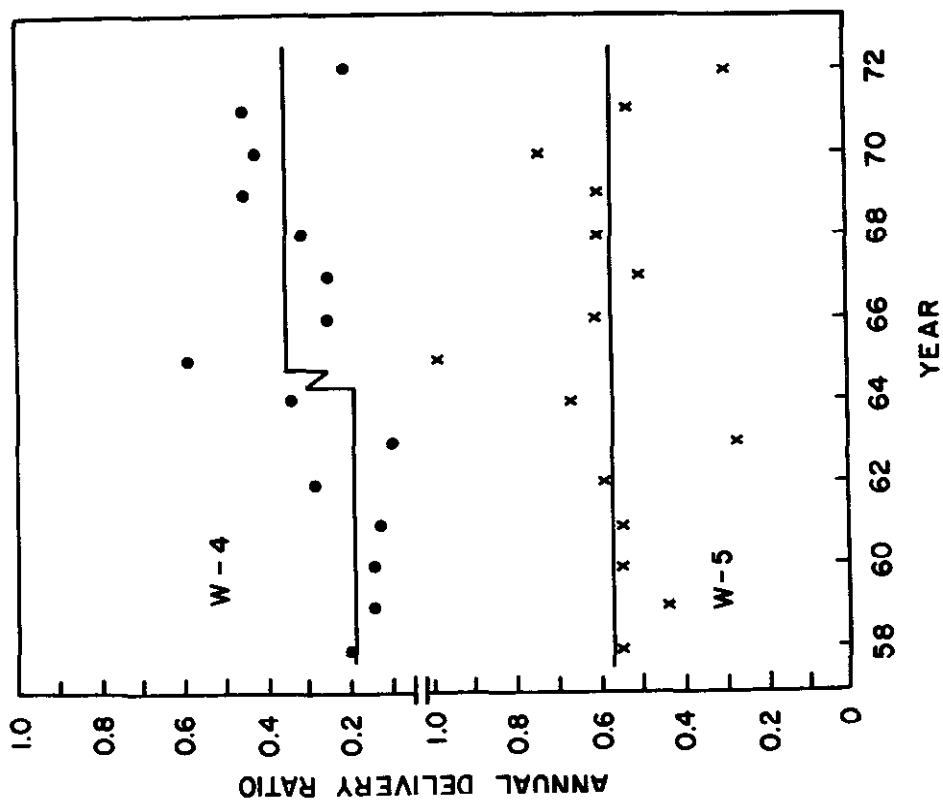


Figure 2. Annual delivery ratios of erosion from all sediment sources in the contributing areas. Total area in W-4 changed from 809 ha (2000 a) to 639 ha (1580 a) after the 1964 wateryear.

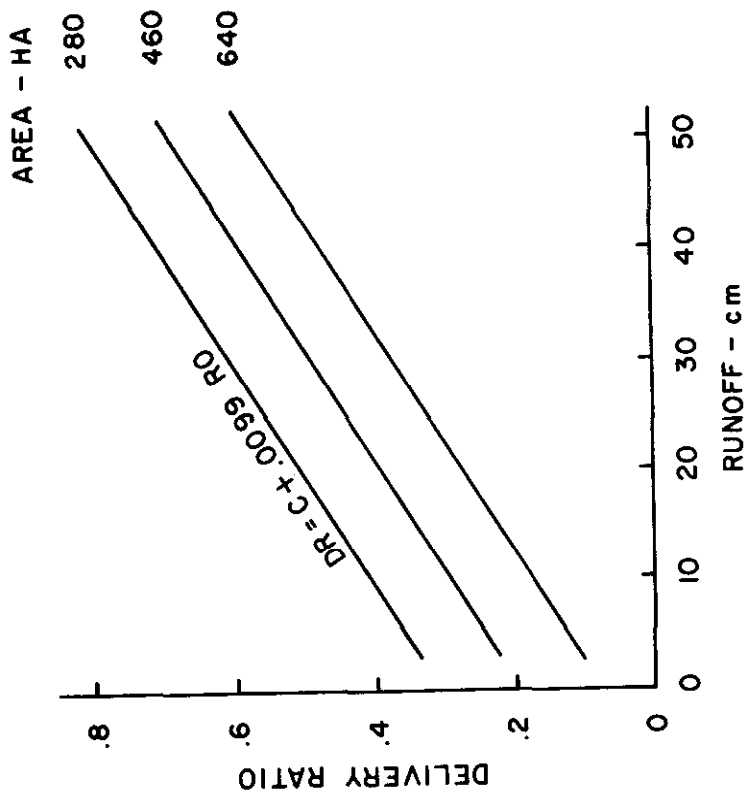


Figure 3. Solution display of Equation 4.

Figure 2 also shows that a change in watershed size changes the delivery ratio as several researchers have noted.

Preliminary examination of the data also indicated a linear effect on delivery ratio of runoff. Therefore, a multiple regression analysis including annual runoff was made. A watershed identification variable was included to determine if the data from both watersheds could be properly examined together. The annual calculated erosion potential was also included to determine if land use had an effect on delivery ratio; erosion potential was A/R of the USLE. The summary table of the analysis follows:

<u>Variable</u>	<u>r²</u>	<u>r² increase</u>
Runoff	.67	.67
Contributing Area	.76	.09
Erosion Potential	.78	.02
Watershed	.79	.01

Neither the watershed nor potential erosion variable contributed much to explaining variation in delivery ratio. The watersheds performed quite differently (Bowie, 1975); runoff and sediment yield from W-5 was much greater than would usually be attributed to the small size difference of the watersheds. However, these differences were reflected in the strong runoff variable and the weaker area variable.

Obviously, the major contributing variables were runoff and contributing area. The equation including these variables is

$$DR = 0.488 - 0.00064 \text{ Area} + 0.0099 \text{ RO} \quad (3)$$

with area in hectares and runoff in centimeters. This equation covering the range of the data is also shown in Figure 3.

Statistics from the multiple regression analysis showed that land use represented by erosion potential was poorly correlated with runoff ($r = .05$). This is further illustrated by the data in Figure 4 showing the poor correlation of runoff as a percent of rainfall and predicted sheet erosion.

CONCLUSIONS

Factors other than land use, contributing area, conservation structures, and runoff discussed above also influence sediment delivery ratios. Among these are the morphological features of a watershed, drainage area size and relief/length ratio, as suggested by Roehl, 1962. Continued analysis of results from other subwatersheds of Pigeon Roost will allow consideration of these factors and refinement of the conclusion of this paper.

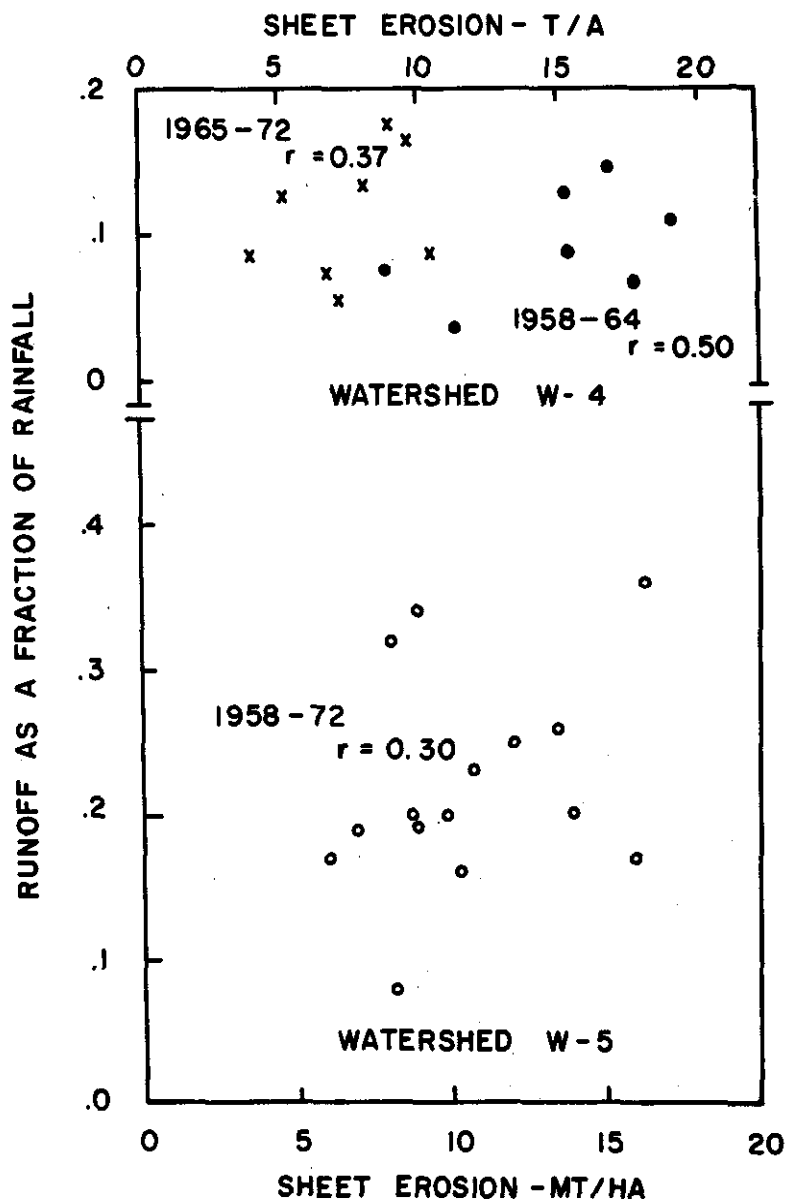


Figure 4. Effect of land use, represented by annual sheet erosion estimates, on annual runoff.

Land use changes had little effect on sediment delivery ratios from the two watersheds--one with increasing soil-conserving land use and the other with decreasing soil-conserving land use; thus, land use causing decreasing erosion estimates resulted in decreasing sediment yield under constant rainfall conditions as expressed by the rainfall factor, R, of the USLE. However, conservation practices like gully plugs, sediment detention structures, and flood control dams, reduced potential sheet erosion by one-third in each watershed.

Delivery ratios were higher for years of larger runoff, suggesting use of a runoff factor in predicting sediment yield. Annual values of estimated erosion did not seem to have any effect on delivery ratios.

ACKNOWLEDGEMENTS

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WATERSHED EROSION MODEL VALIDATION FOR SOUTHWEST IOWA

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ABSTRACT

Watershed erosion data from two ARS watersheds near Treynor, Iowa are used to test an erosion model developed by Onstad and Foster (1975). This model utilizes a distributed set of input variables and includes a detachment and a transport phase. Depending on the magnitude of each phase, soil is either eroded or deposited. Predicted sediment yields from sheet-rill sources were compared with measured yields for single events and with predictions by the universal soil loss equation developed by Wischmeier and Smith (1965) and the Williams model (1972). A sensitivity analysis was performed for the fitted parameter in the Onstad-Foster model. Confidence intervals were also calculated for a wide range of single-event sediment yields.

INTRODUCTION

Erosion modeling for agricultural watersheds is rapidly being developed to meet guidelines for identifying and evaluating the nature and extent of agricultural pollution. Some models use fundamental fluvial hydraulic and hydrologic theories and others apply established empirical techniques. Prediction needs range from upslope erosion distribution on a storm basis for small watersheds to average annual sediment yields from large watersheds. A single model probably will not be suitable for all purposes nor universally applicable for a single purpose.

The model explained here and tested against two other models was designed to estimate the upslope erosion and sediment yield from small watersheds in the Corn Belt for single rainfall events. A mathematical procedure is described to estimate soil detachment and transport from each soil-slope unit of a system of units representing the watershed geometry. Sediment yields predicted by this model are compared with measured quantities for two watersheds near Treynor, Iowa and with estimates obtained by using two other prediction methods.

DESCRIPTION OF MODEL

This erosion model consists of relationships describing the two phases of the erosion process, detachment and transport. It has been described in detail by Onstad and Foster (1975) and Frere, et al. (1975). The basic equation used is the Universal Soil Loss Equation (USLE) with modifications described by Foster, et al. (1973).

A = WKCPSL

[1]

where A is the soil loss in tons/acre (T/a), W is a hydrologic term and K, C, P, S, and L are the usual USLE parameters. The hydrologic term, W, is a function of both rainfall and runoff.

$$W = a R_{st} + (1 - a) 30 Q q_p^{1/3} \quad [2]$$

where R_{st} = storm rainfall factor (EI units of the USLE)
 Q = runoff volume (in)
 q_p = peak runoff rate (in/hr)
 a = coefficient ($0 \leq a \leq 1$)

The numerical constant, 30, was evaluated from plot data obtained with artificial rainfall on 20 soils in Minnesota and Indiana (Foster, et al. 1973). The coefficient, a , represents the relative importance of rainfall energy compared with runoff energy for detaching soil. Normally, a will be larger for watersheds having short slopes, no vegetative cover, and intense rains. Until more research is conducted, a must be evaluated by measured sediment yields.

The sediment yield for a complex slope depends on the detachment and transport of soil from upslope. If several approximately uniform segments represent the slope, Foster and Wischmeier (1974) have shown that the detachment capacity can be represented by

$$E_j = \frac{W_j(KCPS)_j}{185} (x_j^{1.5} - x_{j-1}^{1.5}) \quad [3]$$

where E_j = detachment capacity for segment j (lbs/ft width)
 x_j = distance from top of slope to lower end of segment j (ft), and all other terms are as described for equations [1] and [2]

Each slope segment may have a unique set of parameters, as shown in equation [3]. When a slope has n segments, the total detached soil capacity is the cumulative amount of all segments and this equals the slope sediment yield, provided that the soil transport capacity is not limiting.

The transport capacity used in this model is represented by the equation

$$T_{xj} = \frac{W_j(\tau SCP)_j}{185} x_j^{1.5} \quad [4]$$

where T_{xj} = transport capacity at position x_j (lbs/ft width).
 τ = transportability

Values for S, C, W_j , and P are the same as those used for calculating detachment.

Throughout this discussion, τ is assumed to be the same as K. If a slope has more than one soil type, τ is evaluated by calculating the average detachment weighted erodibility of each soil. This value reflects the transportability of material from upslope segments across the segment being evaluated.

Sediment yield is calculated to the bottom of each slope segment by comparing the total soil detachment and the transport capacity. If transport capacity exceeds the detached load of the segment plus

contributions from upslope segments, then sediment yield is the sum of the detached load plus upslope contributions. If the transport capacity is less than the total soil available to be transported, the sediment yield equals the transport capacity and the remainder of the soil is considered to be deposited. Calculations are begun for the uppermost segment and continued until the channel is reached. The sediment yield for the watershed is assumed to be the sum of the yields of all the streamtubes at the channel. All sediment contributions reaching the channel are assumed transported from the watershed. The final results are the storm sediment yield from the watershed and the distribution of erosion throughout the watershed.

TESTING PROCEDURE

The sediment data used for model testing were obtained from Watersheds 1 (74.5 a) and 2 (82.8 a) of the Agricultural Research Service near Treynor, Iowa (Saxton, et al., 1971). These watersheds are single-cropped and typical of the deep loessial soil region of western Iowa. Detailed hydrologic and sediment data are available for each major event. These data include rainfall, hydrographs and sediment loads.

To divide the watershed into a series of slopes, we drew flow lines on topographic maps of the two watersheds. These flow lines were selected to separate different regions with respect to overland flow characteristics as described by Onstad and Brakensiek (1968). Each area between adjacent lines constitutes a complex slope along which detachment and transport capacities were calculated with equations [3] and [4]. The slopes were divided into segments to represent the major gradients. Each segment is considered to be homogeneous with respect to W , K , C , P , and S . The streamlines selected to represent the two watersheds are shown in Figures 1 and 2.

Watershed 1 was divided into 30 complex slope units and Watershed 2 into 48 units. The area and the length of the contour boundaries of each unit were measured, and the average slope length was determined by assuming each unit to be trapezoidal. Average slope gradient for each segment was determined by measuring the length and relief of a transect drawn within each segment. These geometric parameters allow computation of S and x of equations [3] and [4] for each slope.

Both watersheds are composed of Ida and Monona soils, using a soil erodibility factor, K , of 0.32. The practice factor, P , was assumed to be 1.0, because the contour farming was not effective. The cropping-management factor, C , was determined from Wischmeier and Smith (1965), using crop stage periods averaged over the years investigated.

Ideally, the runoff parameters, Q and q_p , for a particular storm would be estimated by using a reliable hydrologic model at all points needed on the watershed and the rainfall factor, R_{st} , would be determined from a rainfall histogram. The data available from these watersheds included rainfall histograms for determining R_{st} , the outlet hydrograph for determining Q and q_p , and the sediment yield from sheet-rill sources. Throughout the testing procedure, both the rainfall factor, R_{st} , and the runoff volume, Q , were assumed to be uniformly distributed over the

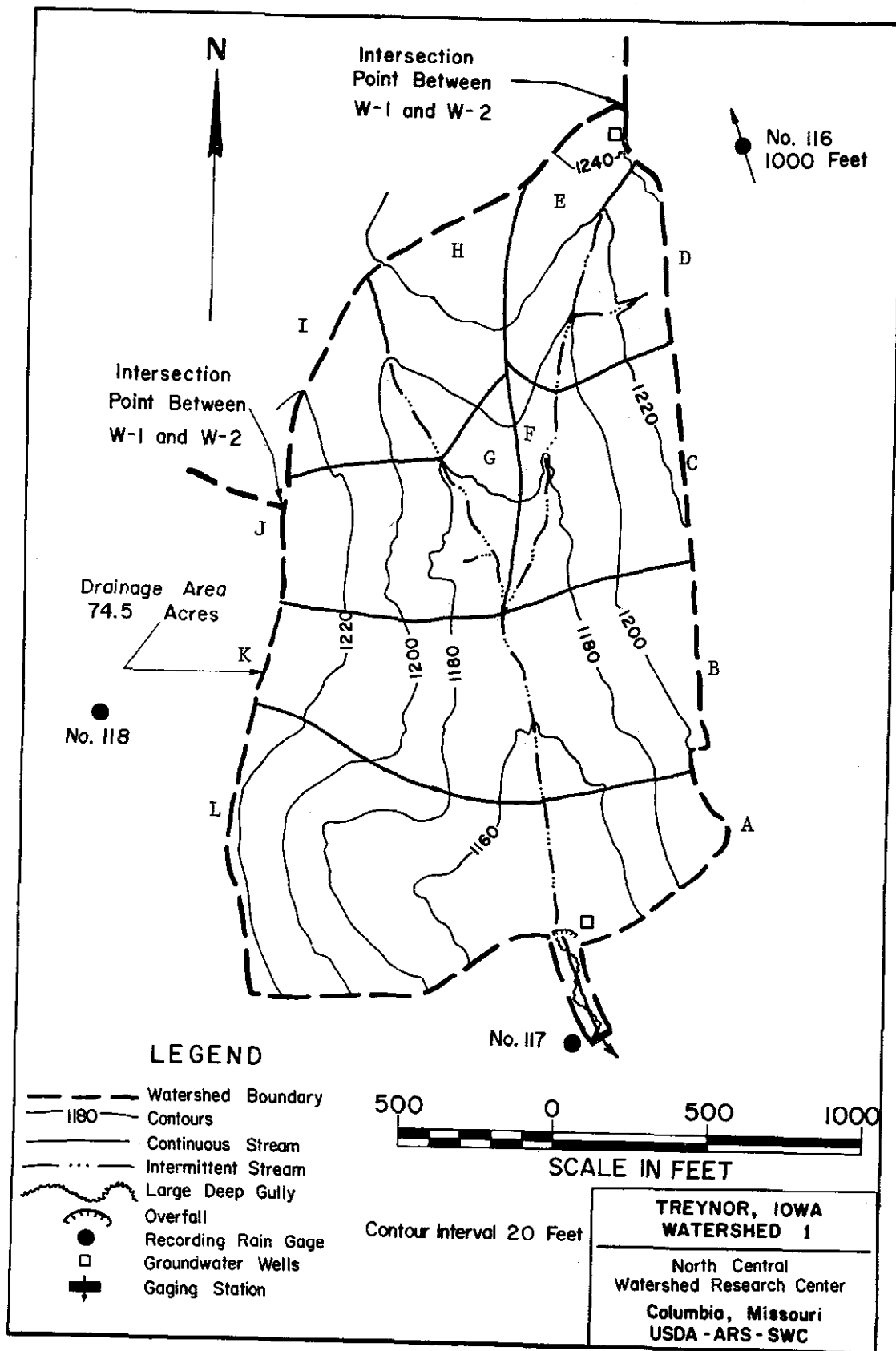


Figure 1

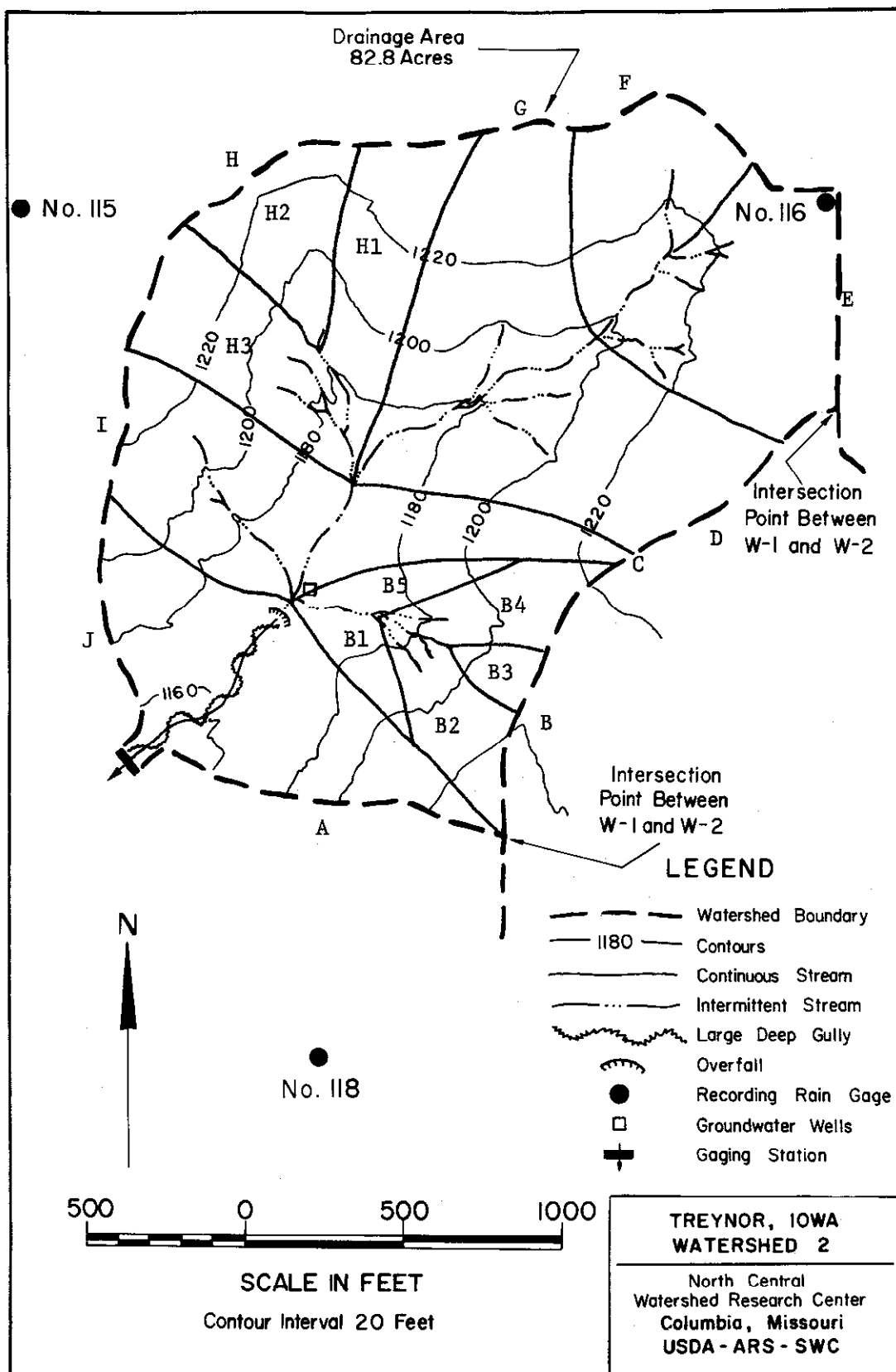


Figure 2

watershed so that these factors were constant and uniform for all segments.

The peak rate of runoff, q_p , was estimated at the bottom of each segment by using a weighting factor together with the measured peak rate from the watershed. Several resistance formulas, such as Manning's and Chezy's, use area or the square root of the slope gradient as independent prediction variables. Consequently, the peak flow rate weighting factor for each segment was $a_s s^{1/2}$, where a_s is the segment area and s , the slope gradient. If the segment bordered the divide, its weight was that calculated. Proceeding downslope, the weighting factor was accumulated for each segment encountered. The peak flow rate for each segment was then calculated to be the product of the measured watershed peak flow rate and the accumulated weighting factor.

The parameter, a , of equation [2] was determined for each watershed by minimizing the variance between measured and predicted sediment yield for half of the selected events. The selected events were those considered to be well sampled in terms of sediment concentration for 1965 through 1972 -- 62 storms on W-1 and 48 storms on W-2. The parameter, a , was determined for W-1 and W-2 separately and then combined because the watersheds are similar in location, soils, topography, and crop. The optimization was done to minimize the sum of the squared deviations expressed as

$$SD = \sum_{i=1}^n (\hat{Y}_i - Y_i)^2 \quad [5]$$

where $\hat{Y}_i$ is the estimated sediment yield and Y_i , the measured yield. The results of these optimizations for the a value are shown in Table 1. The values of a determined by optimizing yields were 0.14 for W-1 and 0.08 for W-2, and their combined value was 0.10.

Table 1. Results of optimization runs for the determinations of a

	a	Sum of squared deviations		r^2 (all events)
		First half events	All events	
W-1	0.14	36.68	82.86	0.97
W-2	0.08	15.86	98.18	0.96
W-1 and W-2	0.10	54.50	252.60	0.94

Figure 3 shows the sensitivity of the fitted parameter, a . The curve indicates the amount of error to be expected when the value of a is varied. For example, for a range in a from 0.05 to 0.15, the change in squared deviations is 10 percent or less.

Tables 2 and 3 list each event and its measured sediment yield for Watersheds 1 and 2, respectively. The measured sediment yields range from 0.01 to 49.72 tons/acre. Also listed are individual predicted sediment yields and associated SD using the Onstad and Foster model described previously. The storms used in obtaining the value of a were events

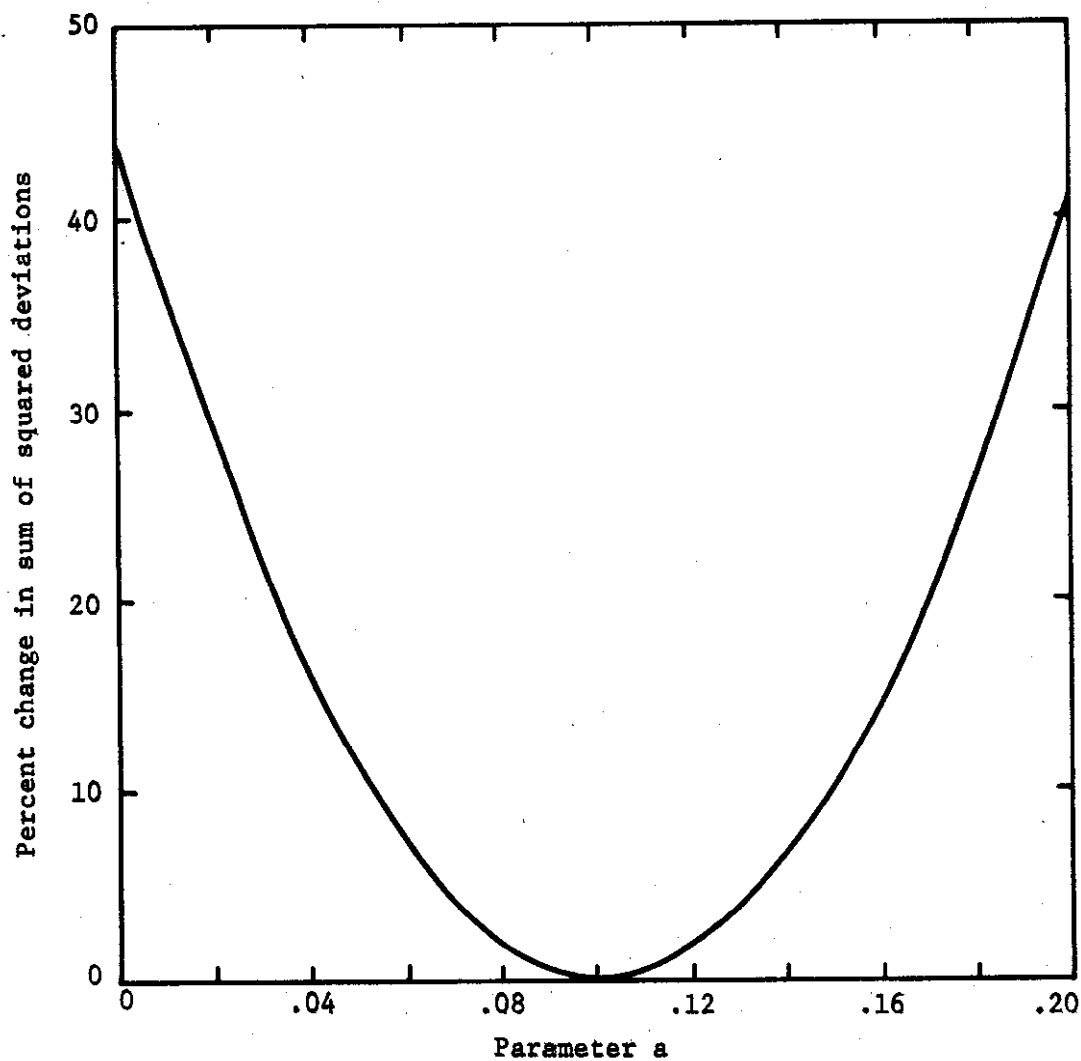


Figure 3. Sensitivity of parameter a

1 through 31 on Watershed 1 and 1 through 24 on Watershed 2. Neither of these intervals included the large storm of June 20, 1967. Deposition was calculated on six of the segments in each watershed. These values, as pointed out earlier, are those obtained using the combined watershed optimized value of a equals 0.10. All other storms on these two watersheds can be considered to be predicted because they did not enter into any parameter determinations.

The Williams model for sediment yield (1972) is expressed as

$$G = \alpha(Qq_p)^\beta \text{ KLSCP} \quad [6]$$

where G = sediment yield for an individual storm (tons)
 Q = runoff volume (acre-ft.)
 q_p = peak flow rate (cfs)
 α, β = model parameters

and $K, L, S, C,$ and P are as defined previously.

This is a lumped model, because constant average values of $K, L, S, C,$ and P

Table 2. Comparison of measured sediment yields with those predicted by three models, Watershed 1, Treynor, Iowa.

Event No.	Measured sediment yield	Onstad and Foster model		Williams model		USLE	
	(T/a)	Yield (T/a)	Deviation squared	Yield (T/a)	Deviation squared	Yield (T/a)	Deviation squared
1	3.81	1.77	4.16	0.88	8.58	4.55	0.54
2	6.76	2.87	15.14	3.30	11.97	1.22	30.70
3	0.92	0.69	0.06	0.36	0.31	0.42	0.26
4	1.26	0.67	0.36	0.48	0.61	0.22	1.08
5	3.01	1.95	1.14	1.53	2.19	2.26	0.56
6	1.19	0.54	0.42	0.33	0.74	0.46	0.54
7	0.02	0.03	0.00	0.01	0.00	0.02	0.00
8	0.12	0.18	0.00	0.03	0.01	0.60	0.24
9	2.39	2.35	0.00	1.89	0.25	1.83	0.32
10	1.11	0.64	0.22	0.28	0.69	1.79	0.46
11	4.58	3.39	1.42	2.16	5.86	6.76	4.76
12	0.69	0.53	0.02	0.33	0.13	0.53	0.02
13	0.24	0.17	0.00	0.10	0.02	0.10	0.02
14	0.24	0.73	0.24	0.13	0.01	3.25	9.06
15	0.07	0.17	0.02	0.05	0.00	0.46	0.16
16	0.32	1.04	0.52	0.48	0.03	3.08	7.62
17	0.10	0.26	0.02	0.11	0.00	0.48	0.14
18	0.26	0.73	0.22	0.36	0.01	1.25	0.98
19	0.16	0.20	0.00	0.11	0.00	0.18	0.00
20	1.01	0.87	0.02	0.16	0.72	3.61	6.76
21	0.50	0.37	0.02	0.08	0.18	1.42	0.84
22	4.69	2.43	5.10	2.18	6.30	3.64	1.10
23	15.40	14.80	0.36	10.43	24.70	19.84	19.72
24	13.70	13.64	0.00	18.26	20.79	14.63	0.86
25	1.92	2.64	0.52	2.04	0.01	1.42	0.26
26	2.08	2.33	0.06	2.23	0.02	1.23	0.72
27	1.60	1.80	0.04	1.65	0.00	0.58	1.04
28	7.38	9.74	5.58	9.94	6.55	7.69	0.10
29	1.73	3.26	2.32	2.91	1.39	1.58	0.02
30	3.06	3.39	0.10	4.26	1.44	2.86	0.04
31	0.81	0.81	0.00	0.59	0.05	0.60	0.04
32	49.72	42.29	54.98	42.91	46.38	70.38	417.66
33	0.38	0.46	0.00	0.06	0.10	2.06	2.82
34	2.56	1.45	1.24	0.70	3.46	4.85	5.24
35	0.08	0.81	0.54	0.02	0.00	9.38	86.50
36	0.12	1.48	1.84	0.30	0.03	5.62	30.26
37	0.05	0.15	0.02	0.00	0.00	1.04	0.98
38	0.08	0.26	0.04	0.01	0.00	1.40	1.74
39	0.48	0.70	0.04	0.15	0.11	5.29	23.14
40	6.27	4.50	3.12	1.99	18.32	9.19	8.52
41	0.63	0.30	0.10	0.18	0.20	0.17	0.11

Table 2. Continued.

Event No.	Measured sediment yield	Onstad and Foster model		Williams model		USLE	
		Yield	Deviation squared	Yield	Deviation squared	Yield	Deviation squared
	(T/a)	(T/a)		(T/a)		(T/a)	
42	0.01	0.12	0.02	0.00	0.00	1.29	1.64
43	4.28	5.74	1.14	5.54	1.59	15.78	132.26
44	0.56	0.41	0.02	0.08	0.23	1.60	1.08
45	0.27	0.12	0.02	0.05	0.05	0.13	0.02
46	0.64	0.30	0.12	0.17	0.22	0.17	0.22
47	0.98	0.52	0.20	0.34	0.41	0.36	0.38
48	0.36	0.37	0.00	0.28	0.01	0.13	0.06
49	2.93	1.79	1.30	1.76	1.37	1.29	2.70
50	2.67	2.55	0.02	2.53	0.02	1.90	0.60
51	0.79	0.93	0.02	0.71	0.01	0.52	0.08
52	7.19	9.08	3.56	9.97	7.73	7.45	0.06
53	0.27	0.62	0.12	0.28	0.00	0.20	0.00
54	0.08	0.08	0.00	0.02	0.00	0.17	0.00
55	0.50	0.83	0.12	0.20	0.09	3.81	10.96
56	0.14	0.30	0.02	0.01	0.02	1.54	1.96
57	5.31	1.64	13.44	1.67	13.25	1.22	16.72
58	0.36	0.24	0.02	0.11	0.06	0.08	0.08
59	0.04	0.06	0.00	0.01	0.00	0.03	0.00
60	0.07	0.25	0.04	0.01	0.00	1.32	1.56
61	0.04	0.08	0.00	0.01	0.00	0.30	0.06
62	0.01	0.16	0.02	0.00	0.00	1.84	3.34

Table 3. Comparison of measured sediment yields with those predicted by three models, Watershed 2, Treynor, Iowa.

Event No.	Measured sediment yield	Onstad and Foster model		Williams model		USLE	
		Yield	Deviation squared	Yield	Deviation squared	Yield	Deviation squared
	(T/a)	(T/a)		(T/a)		(T/a)	
1	5.68	2.87	7.92	2.60	9.49	1.84	14.74
2	0.72	0.66	0.00	0.30	0.18	0.30	0.18
3	2.13	1.51	0.38	0.94	0.32	1.31	0.68
4	1.08	0.51	0.32	0.30	0.09	0.30	0.60
5	0.08	0.12	0.00	0.02	0.00	0.27	0.02
6	0.51	0.44	0.00	0.06	0.20	1.58	1.14
7	1.84	0.97	0.76	0.55	1.66	1.54	0.10
8	5.36	4.76	0.36	3.53	3.35	5.72	0.14
9	3.65	4.20	0.30	3.29	0.13	4.74	19.14
10	0.58	0.54	0.00	0.35	0.05	0.29	0.08
11	0.15	0.15	0.00	0.07	0.01	0.09	0.00

Table 3. Continued.

Event No.	Measured	Onstad and Foster		Williams		USLE	
	sediment	model		model			
	yield	Yield	Deviation squared	Yield	Deviation squared	Yield	Deviation squared
	(T/a)	(T/a)		(T/a)		(T/a)	
12	0.29	1.20	0.82	0.46	0.03	2.93	6.98
13	0.40	1.22	0.66	0.52	0.01	2.03	2.66
14	0.05	0.15	0.02	0.05	0.00	0.22	0.02
15	0.20	0.62	0.18	0.28	0.01	0.85	0.42
16	0.06	0.43	0.14	0.11	0.00	0.73	0.44
17	0.04	0.10	0.00	0.02	0.00	0.19	0.02
18	0.05	0.16	0.02	0.05	0.00	0.25	0.04
19	2.18	1.04	1.30	0.32	3.46	2.53	0.12
20	1.06	0.58	0.24	0.17	0.79	1.53	0.42
21	3.44	2.76	0.46	2.28	1.35	3.11	0.10
22	14.70	15.01	0.10	8.88	33.87	19.91	27.14
23	10.00	11.55	2.40	12.28	5.20	13.21	10.30
24	1.65	1.85	0.04	1.13	0.27	0.97	0.46
25	2.62	1.90	0.52	1.62	1.00	0.78	3.34
26	1.30	1.53	0.06	1.22	0.01	0.47	0.68
27	8.13	11.25	9.74	12.41	18.32	5.66	6.10
28	3.08	3.10	0.00	3.07	0.00	2.42	0.44
29	1.35	1.04	0.10	0.78	0.32	0.70	0.42
30	29.10	38.69	92.02	33.63	20.52	55.08	674.96
31	0.40	0.38	0.00	0.03	0.14	1.68	1.64
32	3.43	1.98	2.10	1.10	5.43	4.41	0.96
33	0.04	0.75	0.52	0.01	0.00	6.64	43.56
34	0.03	0.06	0.00	0.01	0.00	0.18	0.02
35	0.06	1.91	3.42	0.32	0.07	6.13	36.84
36	0.39	0.67	0.08	0.09	0.09	4.25	14.90
37	0.63	0.40	0.06	0.21	0.17	0.22	0.16
38	0.04	0.41	0.14	0.01	0.00	1.90	3.46
39	2.05	4.36	5.34	3.15	1.21	9.95	62.42
40	0.08	0.04	0.00	0.01	0.00	0.10	0.00
41	0.30	0.12	0.04	0.03	0.07	0.18	0.02
42	0.34	0.23	0.02	0.09	0.06	0.28	0.00
43	1.90	1.22	0.46	0.98	0.85	1.15	0.56
44	0.99	0.91	0.00	0.47	0.27	1.26	0.08
45	0.34	0.36	0.00	0.15	0.04	0.43	0.00
46	6.34	6.18	0.02	6.23	0.01	3.85	6.20
47	0.01	0.00	0.00	0.01	0.00	0.03	0.00
48	0.14	0.17	0.34	0.06	0.01	2.70	6.56

are applied to the entire watershed. Only sediment yield predictions at the watershed outlet are calculated. Therefore, once the parameters have been evaluated, equation [6] must be calculated only once for each event.

Williams (Personal Communication, June 23, 1975) has calculated average SL values for Watersheds 1 and 2 to be 1.38 and 1.29, respectively. By using C values that depended on storm dates and assuming P equals one, he obtained the following equation by nonlinear least squares optimization for 213 events on W-1 and W-2.

$$G = 7.24 (Qq_p)^{0.84} \text{ KLSCP} \quad [7]$$

The coefficient of determination was 0.93. Tables 2 and 3 include the results using Williams model as evaluated by equation [7].

The last set of data on Tables 2 and 3 depicts the predictions of these same storms using the USLE. The USLE parameters were determined in the same manner as in the Williams model. A sediment delivery ratio was not used because, of the 110 storms shown in Tables 2 and 3, the sediment yield from 45 was already underestimated by the USLE.

COMPARISON OF THREE MODELS

Several comparisons of results obtained with the three models are shown in Table 4. The first column lists the SD for the storms over which the parameter α was calculated in the Onstad-Foster model (OF) for both watersheds taken together. This value is minimum. The corresponding minimum value for the Williams model would probably be those utilizing all the storms, since about this number of storms were used to calculate α and β for each of the watersheds. All fittings for the USLE were previously done in its development using other data from small plots.

Table 4. Comparisons of different models for computing sediment yields at Treynor, Iowa.

Watershed 1

Models	Summation of squared deviations (SD)					Best Events	Events*
	Events:	1-31	32-62	1-62	1-62*	56 0.10T/a events or less (12 events)	5.0 T/a or more (7 events)
Onstad and Foster Model		38.08	83.12	121.20	66.22	22.80	0.70 41.20
Williams Model		93.56	93.69	187.25	140.87	51.84	0.00 103.31
USLE		88.96	760.86	849.82	422.16	119.30	96.12 76.68

Watershed 2

Models	Summation of squared deviations (SD)					Best Events	Events*
	Events:	1-24	25-48	1-48	1-48*	43 0.10T/a events or less (11 events)	5.0 T/a or more (6 events)
Onstad and Foster Model		16.42	114.98	131.40	39.38	12.96	4.26 20.54
Williams Model		60.48	48.61	109.09	88.57	21.46	0.07 70.24
USLE		85.94	863.32	949.26	274.30	104.34	84.42 64.62

*Omitting storm of June 20, 1967.

The third column of Table 4 shows the results of the three models for all storms. Because a large amount of deviation is associated with the extreme event of June 20, 1967, the data in column four shows the results with this storm omitted. About 50 percent of the total variation in the OF model and USLE was due to this storm and about 25 percent in the Williams model for W-1. The total error variance of the OF model is about one-half of that for the Williams model and about one-sixth of that for the USLE.

Often it is contended that just a few outlying points unduly influence the results of a statistical analysis. To check that effect here, the worst fits, 10 percent of the storms, were excluded. When this was done, the average variance per storm for all the models decreased. The decreases on Watershed 1 were from 1.95 to 0.41 for the OF model, from 3.02 to 0.93 for the Williams models, and from 13.71 to 2.13 for the USLE. Reductions in variance on Watershed 2 were similar. Again, the smallest amount of variance is associated with the OF model.

Because the energy term in the Williams model is associated only with runoff and that for the USLE is associated only with rainfall, difference in degree of fit may be associated with the magnitude of the runoff. Columns six and seven of Table 4 show the summation of variance for the small and large runoff events, respectively. The Williams model predicts the small events on both watersheds very accurately. The USLE predicts these small storms very poorly. For the large storms, the opposite is true. This suggests that runoff characteristics are the major influence on sediment yields for small storms and rainfall characteristics are the major factors for the large storms. In general, Table 4 clearly illustrates that a model containing an energy term that combines rainfall and runoff is superior to one containing only a rainfall or a runoff factor.

A linear regression of measured versus predicted sediment yield by the OF model using the data in Tables 2 and 3 (measured and OF predicted values), had a slope of 0.97 ± 0.05 at the 95 percent confidence level and an intercept of 0.06 ± 0.31 at the 95 percent level. Throughout the range of measured values, the 95 percent confidence belt includes the line of equal values.

Table 5 shows the confidence range and the percent of the estimated value. For predicted values of less than 0.25 tons per acre, the confidence belt is about ± 100 percent or larger. For larger values, the confidence belt narrows so that at a predicted value of 1.0 ton per acre, the range is about ± 30 percent, and further decreases to a constant width of about 10 percent at predicted values of between 5 and 10 tons per acre.

SUMMARY

Validation tests of the Onstad-Foster (OF) sheet-rill watershed erosion model on two watersheds in southwest Iowa showed encouraging results. The model predicts sediment yield from single storms. The storms tested produced sediment yields from 0.01 tons per acre to nearly 50 tons per acre. In general, the OF model predicted storm sediment

quite accurately. Also shown were sensitivity relations for single fitted parameter in the OF model and confidence intervals throughout the range of predicted even events. The results from the OF model were compared with the Williams model and the USLE. These results showed that OF model performed better than the other two models for the storms tested.

Table 5. Confidence limits about the line of equal values for the Onstad-Foster Model on Watersheds 1 and 2, Treynor, Iowa.

sediment yield (T/a)	95% confidence limits			
	Lower limit		Upper limit	
	Tons/acre	% of estimate	Tons/acre	% of estimate
0.25	0.00	-100	0.59	136
0.50	0.23	- 54	0.83	66
1.00	0.73	- 27	1.31	31
2.00	1.71	- 14	2.27	14
3.00	2.68	- 11	3.24	8
5.00	4.60	- 8	5.20	4
10.00	9.31	- 7	10.19	2
20.00	18.59	- 7	20.31	2
50.00	46.32	- 7	50.78	2

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RESERVOIR SEDIMENTATION ASSOCIATED WITH CATCHMENT ATTRIBUTES LANDSLIDE POTENTIAL, GEOLOGIC FAULTS, AND SOIL CHARACTERISTICS*

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ABSTRACT

Deposition measurements in 48 northern California reservoirs were found related to precipitation amount, rain-snow frequency, road standards and location, forest fires, geology, and physiography, and also to differences among watersheds (catchments) in landslide classes, extent of geologic faults, clay content of watershed soils, and density of reservoir sedimentation. The data were analysed by reduced rank principal component techniques. The final regression equation had an explained variance of 0.86 and a standard error of 0.138 log units. Difference in average annual deposition associated with reservoir density was 39 percent; with landslides, 100 percent; with faults, 41 percent; and with clay in watershed soils, 32 percent. Some geologic rock types with geologic faults and high landslide potential had a predicted sediment rate as much as 17 times that of areas without faults. Roads located near streams contributed the most to deposition--twice as much as did roads located elsewhere. And improved secondary roads near streams were the single greatest contributor, especially in area of steep terrain. Roads in steep topography produce twice as much acceleration in sedimentation as do those in less steep terrain. Preliminary appraisal of bedload (difference between reservoir deposition and suspended sediment discharge) indicate it varies from 90 percent to less than 20 percent of "total load" in different areas.

*This paper quotes from and uses much of the same material in two of the author's earlier papers: Anderson 1974, Anderson 1975c. Copies of these papers are available upon request to the Station.

INTRODUCTION

In this paper, I will repeat much of the same material in two of my earlier papers (Anderson 1974, 1975c). As I pointed out (Anderson 1975c):

" 'The only estimates of sedimentation that have quantitative credibility are those that employ the results of multivariate analyses of sedimentation from watersheds.' So concluded a recent U.S. Forest Service study group that investigated quantification of erosion and sedimentation¹. Why such a conclusion and what are the attributes of analyses that led to such a conclusion? Perhaps an analysis of reservoir deposition by means of regression on principal components will offer some answers. First, the system multiple watersheds being analysed can be thought of as being "distributed" in a unique way: By studying many watersheds with wide differences we have incorporated the variability in inputs that we wish to analyze. These differences include types and amounts of meteorological inputs, static attributes such as geology and topography, and dynamic attributes such as land use. Second each combination of variables is associated with a measured consequence--sediment deposition in a reservoir. And third, reduced rank principal component analysis has proved to be a powerful tool in determining the quantitative contribution of each variable to that deposition. Thus, by expressing time variations of sediment causes and space variation of sediment sources as variables and relating these to the resultant differences in sediment deposition, we can predict the rate of sedimentation and suggest where sediment control will be the most effective.

"Being the sum of both suspended load and bedload, a measurement of reservoir deposition corrected for trap efficiency provides the only valid estimate of total sediment discharge from catchments. Measured deposition in reservoirs can vary widely."

My two earlier papers (Anderson 1974, 1975c) showed that deposition in 48 reservoirs in northern California ranged from 8 to 84,000 m³/km²/yr, with periods of deposition measurement ranging from a single year to 70 years. The wide differences I attributed to catchment characteristics and climate during the deposition period. In the first study (Anderson 1974), I used 21 variables to denote the static and dynamic characteristics of watersheds. In the second study (Anderson 1975c), I added 10 variables to the 21 used in the first study.

This present paper also reports a separate study of the interaction between road standards and location and steepness of watershed terrain. In addition, it provides a preliminary appraisal of bedload

¹/Report of the Committee on Quantification of Erosion and Sedimentation, Watershed Management Workshop for Earth Science specialists, Region V, U.S. Forest Service, Fresno, Calif., February 25-27, 1975.

in the Sierra Nevada contrasted with that in north coastal California. The analytical methods used in this separate study and preliminary appraisal were identical to those used in the second study (Anderson 1975c), which I described as follows:

ANALYTICAL METHODS

"The relation of sediment deposition to catchment, streamflow, and land-use variables was studied by using this general model:

Reservoir deposition = f (topography, geology, roads, forest fires, streamflow, precipitation, soil, landslides, and geologic faults).

The analytical technique I used was principal components analysis, consisting of a factor analysis of the correlation matrix, Varimax rotation of the factors, and regression on a reduced rank matrix (Wallis 1965). The initial factor test consisted of 36 independent variables, and these were reduced to 21 on the basis of independent loading. Two of the 10 road variables--ST 12 and ST3--failed to load independently. Excepting those two variables, the independent effects of each variable may be interpreted from the regression results.

"The initial regression, done in an earlier study, was performed by using 69 measurements of reservoir deposition and associated 21 catchment attributes (Anderson 1974). That equation had an explained variance of 78 percent. The current regression utilized the deposition calculated from that equation as a variable and added 10 others. However, the coefficients for these added variables were derived from the complete 34 variable matrix. The extended equation included evaluation of (a) landslide classes identified by the U.S. Geological Survey (Radbruch and Crowther 1973); (b) extent of faults shown on State of California (1966) geologic maps; (c) mean annual precipitation (U.S. Geological Survey 1969); (d) reservoir density predicted from geology-soil-texture relations (Wallis-Willen 1963) and from texture-density-age relation (Koelzer and Lara 1958); and (e) clay content of the surface soil estimated from geology and adjusted for climate (Wallis and Willen 1963). Use of the additional variables helped increase explained variance from 78 to 86 percent and decrease the standard error from 0.335 to 0.138 log units. Factor contributions to explained variance were: landslides and faults, 29; topography, 17; meteorology, 17; geology, 13; roads, 6; and forest fires, 4, for a total of 86 percent.

"The regression model consisted of a log transformation of most variables not already expressed as percentages and the log of reservoir deposition expressed in cubic meters per hectare per year. The definitions of the variables, together with the standard deviation, s.d., and the means of each variable and the regression coefficients, are given in Table 1.

"REGRESSION RESULTS

"Despite the wide variation in contributions of catchment sediments to reservoir deposition, the major sources of variability may be estimated from the coefficients (Table 1).

"Geologic differences are discernible, with the unconsolidated sediments (sediments Cenozoic and younger) being the greatest sediment producers. The relative production of reservoir deposition, with Basalt considered 1.0, was: granitic rocks, 1.3; precenozoic marine sediments and metamorphic rocks, 1.6; and marine sedimentary rocks, Cenozoic and younger, 4.7.

"Topographic variables of elevation, slope of tributary streams, and shape of catchment show difference in sediment deposition, with elevation best portrayed by its effect on the frequency of rain versus snow (SA). High elevation catchments have less than 0.1 times as much deposition as low elevation ones, other factors being accounted for. Slope of tributary streams (SL) produced difference in reservoir deposition by a factor of 4. Shape of catchment (CV) was least effective, only a 17 percent difference in sediment deposition between catchments."

In the second study (Anderson 1975c), I described other results as follows:

"Streamflow varied widely among the different periods of deposition measurement. To evaluate this source of variability, I selected 10 streams to serve as indexes of year-to-year streamflow sediment potential. The records of streamflow were found to be time invariant by double-mass analysis. The records were then extended where needed to the full 1891-to-1965 period (Anderson 1975b). The streamflow sediment potential calculated for each stream was a function of three streamflow characteristics for each year and was expressed by the mean annual flow times the maximum daily flow divided by the 75-year (1891-1965) average of that product. Hence, the sediment potential for average year (RSP) was 100. The index is a simple indication of sedimentation potential found by regression analysis in a study in Oregon (Anderson, 1954). For each reservoir deposition and each period, one of the nearby index streams was chosen and its average RSP for those years involved in the deposition were taken as the RSP variable. Inclusion of such a variable is essential for the RSP in periods of 20 years or more can deviate widely from long-term average: In the 20-year period 1919-1939 for the Bullard Bar catchment it was only 62 percent of normal. In contrast, in the 21-year period 1948-1969 in the Juncal catchment, RSP was more than twice that of normal. The range in RSP of 7 to 630 produced periodic differences in expected sediment by a factor of 4.85.

"Forest fires occurring before or within the sediment measurement period may play a role in augmenting reservoir deposition. This role was established in studies of suspended sediment discharge from northern California streams (Wallis and Anderson, 1965) and for reservoir deposition in southern California catchment (Anderson, 1949). As a first approximation to fire effects on deposition, the fires in the

26 years antecedent to each year of deposition was used. Since this variable is in effect a 26-year moving average of annual burns, it is a useful index for management evaluation. Forest fire differences between catchments were associated with an increase in deposition by a factor of 2.

"The effects of old fires and to some extent those of newer fires in areas where fire history was not readily available were represented by large high-elevation brushfields. These brushfields probably originated from repeated burns, often set by sheepmen in earlier times. The mechanism of their effect on sedimentation may be faster snowmelt (Anderson 1963) or loss of soil and soil resistance to erosion. However, the results suggest that the effect of the range among catchments in the extent of high elevation brush (EBR) produced a 55 percent increase in sediment production in the zone above 1500 m. elevation.

"Roads as they have been located, designed, and maintained in the past contributed heavily to accelerated sedimentation. The emphasis on roads as an index of intensity of land use seems justified by studies in the Western United States (Anderson 1954, Dyrness 1967, Fredricksen 1970, Megahan and Kidd 1972, Wallis and Anderson 1965). This study examined the broadest classification of roads, by three standards, from highways to dirt (earth) roads, and by four locations: ridge, slope, streamside, and urban. The class of roads evaluated encompass some of the major design decisions so the relations to sediment deposition may be helpful in evaluating alternatives.

"Differences in roads explained 6 percent of the variation in reservoir deposition. The average effect of roads (0.6 km roads per km² and average of all coefficients) was to increase deposition by 37 percent. The coefficients of regression of road standards and locations coefficients from the original regression analysis in non-metric units for roads, mi/mi² of catchment) suggest the relative effects of each group on reservoir deposition:

Standard	Location				Relatives
	Ridge (R)	Slope	Streamside(ST)	Average	
Highways	.0600	.0756	.0265	.0540	(1.00)
Surfaced Roads	.1229	-.2494	.8388	.2374	1.53
Dirt Roads	-.0661	.2633	.1877	.1283	1.19
Average	.0389	.0298	.3510		
Relatives	(1.00)	0.98	2.05		

"On the average, highways increased sediment 13 percent (antilog 0.0540, but that secondary improved roads and dirt roads produced 53 and 19 percent more sediment than did highways. Ridge and slope locations in general produced the least accelerated sedimentation, increasing sedimentation only 9 percent; streamside locations produced twice as much sediment as did ridge and slope locations of roads.

"Roads apparently having the least effect were the improved secondary roads on slopes (away from streamside). The worst location was streamside, with roads there increasing sediment by as much as

690 percent. Upgrading the dirt roads to surfaced (with the resultant stabilization of the road surface and improved drainage) at the slope location, promises to reduce sediment by 44 percent. Near streams, upgrading of roads is almost always coupled with major changes in alignment and is a frequent cause of increased sediment production. The dominance of sediment increases from those roads in streamside locations results from massive cut banks and encroachment of fills on the stream channel. Although streamside locations of roads in general produced two times as much sediment as ridge or slope location of roads, the upgrading of dirt roads along streams could increase sedimentation by 380 percent."

In a separate study, by using identical methods to those reported earlier (Anderson 1975c), I related sedimentation to road slope interaction.

Road Slope Interaction. Roads in steep topography produce more acceleration in sedimentation than do those in less steep terrain. The coefficients tabulated above and in Table 1 pertain to the average steepness (SL=21.9 m/km or 21.9 percent).

A separate analysis was made of the interaction of road location and steepness of the terrain, by three locations: ridge roads (R), roads located on slopes (SL), and roads located along streamside(ST). Roads in each location were expressed in miles per square mile, with terrain slope from the variable SL expressed in percent. The resultant equation for change in reservoir deposition, SED, is:

$$\Delta \log SED = k + SL \times (-.00302 R + .00145 SL + .00341 ST)$$

The constant k can be taken from the appropriate coefficient in the road standard and location tabulation.

The equation enables us to assess the effect of terrain steepness on the expected acceleration of sedimentation. For example, for dirt roads at streamside where SL is only 10 percent as against the average of 21.9, the expected acceleration in sedimentation would be 40 percent, $\text{antilog}(0.1877 - (.00341 \times (21.9 - 10))) = 1.40$. In contrast, where terrain is steeper, SL-40 percent, the acceleration in sedimentation would be 78 percent. Improved roads at streamside would have correspondingly greater sediment acceleration in the steeper terrain.

As I pointed out in the second study (Anderson 1975c):

"Such are the proportional effects of roads on sedimentation; the quantitative effects of roads depends on the other potentials, climate, geology, etc. in the roaded area. To estimate the quantitative effects the whole equation of Table [1], including the climatic stress variable must be used.

"Climatic Stress. Mean annual streamflow, mean annual precipitation and rain-snow characteristics were used to evaluate climatic stress. Mean annual precipitation (MAP) alone proved to be nearly as effective an index as streamflow so its relationship is reported here for it is readily available from maps (U.S. Geological Survey 1969). The effect of a range in MAP by a factor of 3, produces only a 39 percent difference in reservoir deposition, when the rain-snow characteristics of the precipitation (SA) had been accounted for (Table 1).

"Density of reservoir sediment is important, for the denser the sediment the less volume it occupies in the reservoir. Density (DEN) was calculated from soil texture relation to geology (Wallis and Willen 1963) and from effects of texture, age of reservoir, and drawdown operation (Koelzer and Lara 1958). Deviations about the mean density of 1.44 g/cc ranged from 1.14 to 1.86 (or from 71 to 116 pounds per cubic foot). By adjusting reservoir volumetric measurements to weight (with correction for trap efficiency), it is possible to compare deposition (as a total delivery) and suspended sediment discharge, with the difference being an independent measure of bedload."

My preliminary appraisal of such differences suggest that many places in the southern Sierra Nevada have 70 to 90 percent of the total sediment load as bedload, whereas bedload comprise less than 20 percent of some places along North Coast streams of California.

Again, I quote from my second study (Anderson 1975c):

"Clay binds the soil and, where water is present, enhances mass movement, such as landslides. The effects of mass movement seem to dominate on the average, for the range in clay--from 8 to 22 percent--was associated with a 32 percent greater sedimentation for soils with the high clay content.

"Landslide Classes. In their map, Radbruch and Crowther (1973) separated six landslide classes. The coefficients of Table 1 indicate that reservoir sedimentation was 95 percent greater in their classes 3 and 4 than in their classes 1 and 2. However, the coefficients for classes 5 and 6 do not emerge in their proper rank. The maximum difference in sedimentation was associated with classes 2 and 3, with class 3 which dominates in the North Coast Range having as predicted sedimentation 120 percent greater than class 2 which dominates in the Sierra Nevada Range. These effects are apparently independent of basic geology, for exclusion of the geology variables did not change the coefficients for the landslide classes; the effects of geologic type and landslides are therefore multiplicative.

"Geologic faults, as measurable from the State of California geologic maps, may augment sedimentation. If a fault zone crossed a 40-acre area, the sedimentation for the 316-meter length of fault involved would be 1.41 times that of a similar area with no fault zone. The combination of a fault with class 3 landslide hazard on unconsolidated marine sedimentary rock type (USED) would produce the most sediment--13 to 17 times that of an area with no faults and class 2 landslide potential on basalt.

"Age of reservoir has a remarkable effect on the average rate of deposition. Overriding the effect of consolidation of sediments with time (which was included in the density variable) was an increase in the sediment rates in newer reservoirs. This increase was indexed

by the regression coefficient for the Y1 variable, which shows rates of relative sediment deposition in reservoirs increasing at about one percent per year since 1900:

<u>Year</u>	<u>Related Sediment Rate</u>
1900	1.00
1920	1.21
1940	1.39
1960	1.56
(1980)	1.71

These relative rates may represent acceleration of sedimentation associated with land-use changes, not associated with forest fires or road development or with similar increases in certain streamflow characteristics such as annual and 10-year maximum floods (Anderson 1975a). The increases could have significance in reservoir planning.

CONCLUSIONS

"By use of measured deposition in many reservoirs with diverse watershed attributes, it is possible to evaluate the independent contribution of time variation of sediment causes and space variation of sediment sources to deposition. Reduced rank principal component analysis has proved to be a powerful statistical tool in testing the independence among the attributes to be evaluated and evaluating their quantitative relation to deposition. Each combination of watershed variables is associated with a measured output--deposition--and a regression coefficient expressing each variables contribution is obtained. The regression results permit prediction of sediment deposition from unmeasured watersheds, estimation of the sediment hazard of land areas with different attributes, and estimation of the effects on sediment deposition of changes in land management, specifically forest fire prevention and road development."

In conclusion, let me add that the wide difference in potential acceleration of sedimentation associated with different road standards and locations on different terrains suggest that this difference needs to be considered in land management decisions. The proportion of sedimentation delivered as suspended sediment or as bedload will vary according to location. Therefore, the criteria used to judge water quality will differ from those used to judge the need for surface or channel erosion control.

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Table 1.--Reservoir Deposition Regression Model, Coefficients, Units, Means and Standard Deviations of Variables

<u>Symbol</u>	<u>Definition</u>
Log SED = -0.270	Regression constant, for deposition in m ³ /Ha/yr. mean log SED=0.53, s.d. 0.2597.
+0043 USED	Area of unconsolidated sedimentary rock types (Cenozoic and younger) pct., mean 31.1, s.d. 36.7.
-.0003 PCEN	Area of Precenozoic meta sediments and metamorphic rocks, pct., mean 30, s.d. 25.
-.0012 GR	Area of granitic rock type, pct, mean 21.1, s.d. 32.5.
-0024 BA	Area of basalt rock, pct., mean 4.5, s.d. 14.0.
-.0128 SA	Mean "long-term" snow frequency (1-Relative Rain Area) (Anderson and Wallis 1965), pct., mean 15.5, s.d. 21.3.
+.3087 Log SL	Slope of streams of 800 m. mesh length. (Anderson 1954) m/km, mean 1.9909, s.d. 0.2970.
+.7831 Log CV	Coefficient of variation of basin flowpath lengths (Wallis and Anderson 1965), with path lengths as suggested by Busby and Benson, (1960), unitless, mean 0.1635, s.d. 0.0188.
+.0011 RSP	Average of yearly mean streamflow times maximum daily flow during period of sediment accumulation divided by long-term, 1881-1965, average, mean 132., s.d. 125.
+.1548 Log EF	Effect of forest fires, annual percent of area burned, linearly depleting to zero effect after 26th year, pct., mean 2.35, s.d. 0.6905.
+.4470 Log EBR	Effect of high elevation large brush fields, percentage of catchment area in brush times percent of area above 1500 meters elevation, pct./10 mean 0.1058, s.d. 0.1355.
+.0965 R12	Length of highways on ridges, km per square km of watershed area, mean 0.035, s.d. 0.100.
+.1216 SL12	Length of highways on slopes, km per square km of watershed area, mean 0.093, s.d. 0.141.
+.0426 ST12	Length of highway near streams, km per square km of watershed area, mean 0.049, s.d. 0.167.
+1977 R3	Length of secondary improved (surfaced) roads on ridges, km per square km of watershed area, mean 0.080, s.d. 0.338.
-4013 SL3	Length of secondary improved (surfaced) roads on slopes, km per square km of watershed area, mean 0.151, s.d. 0.690.
+1.3496 ST3	Length of secondary improved (surfaced) roads near streams, km per square km of watershed area, mean 0.072, s.d. 0.202.

Table 1 (continued)

<u>Symbol</u>	<u>Definition</u>
-.1064 R4	Length of unimproved (dirt) roads on ridges, km per square km of watershed area, mean 0.161, s.d. 0.250.
+.4236 SL4	Length of unimproved (dirt) roads on slopes, km per km ² of watershed area, mean 0.320, s.d. 0.601.
+.3020 ST4	Length of unimproved roads near streams, km per square km of watershed area, mean 0.101, s.d. 0.168.
+.1210 URB	Length of urban roads, km per square km of watershed area, mean 0.037, s.d. 0.130.
+.1397 Log MAP	Mean annual precipitation (U.S. Geological Survey 1969), mm, mean 2.9745, s.d. 0.1492.
+.0255 Log PSQ	Square of log MAP, mm ² , mean 8.8476.
-1.9665 DEN	Average density of reservoir sediment, calculated from geology soil-texture relation of Wallis and Willen (1963) and texture-density-age relation of Koelzer and Lane (1958, Table 5), g/cm, mean 1.44, s.d. 0.0314.
+.0096 CLAJ	Percentage of clay in surface soil, calculated from geology soil-texture relation and adjusted for climate (Wallis and Willen 1963), mean 15.3, s.d. 3.8.
+.0778 Log CW	Capacity of reservoir at year Y1 divided by drainage area DA, m ³ /Ha, mean 2.7420, s.d. 0.7302.
+.0137 Log CWSQ	Log CW squared, mean 7.5186.
-.0011 L1	Percentage of area in landslide class 1 (Radbruck and Crowther 1973), mean 7.0, s.d. 24.9.
-.0014 L2	Percentage of area in landslide class 2, mean 31.0, s.d. 44.9.
+.0021 L3	Percentage of area in landslide class 3, mean 18.3, s.d. 28.4.
+.0012 L4	Percentage of area in landslide class 4, mean 25.5 5.4. 35.7.
-.0008 L5	Percentage of area in landslide class 5, mean 10.6, s.d. 22.7.
-.0004 L6	Percentage of area in landslide class 6, mean 7.6. s.d. 25.0.
+.0591 Log FAUL	Extent of geologic fault zones per unit area of watershed, State of California 1966, m/10 Ha, mean 0.93, s.d. 0.68.
-.5589 Log Y1	Year of first reservoir capacity measurement 1850=0, mean 1.8861, s.d. 0.1546.

SEDIMENT YIELD FROM CONSTRUCTION SITES

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ABSTRACT

Two sediment loading functions were fitted to sediment loss data from eight field studies of construction sites. Both are adaptations of the Universal Soil Loss Equation, and involve an empirically-fitted factor to account for effects of intervening terrain between construction site and point of sediment measurement in a nearby watercourse. One function uses the distance from the foot of the exposed area to the nearest perennial stream, while the second uses the percent of the drainage basin undergoing construction. Comparison of predicted sediment yields (in tons/acre) with observed yields indicates that, for the first loading function, about 54 percent of the predictions fall within a range of ± 50 percent of observed values. Approximately 30 percent of the predictions generated by the second method fall within ± 50 percent of the observed values.

INTRODUCTION

The major pollutant released from construction sites is sediment. Most of the relatively small body of data collected on the release of pollutants by construction activities has concerned sediment and erosion. This is not to ignore the presence of other pollutants in construction runoff -- pesticides, nutrients, heavy metals, oil, and other components of construction wastes -- or the important work being done for estimating concentrations of such pollutants. But, because of the importance of the sediment problem in construction runoff and the general unavailability of data for other pollutants, the present effort to develop source loading functions has been concentrated on sediment release.

APPROACH

Several equations for estimating sediment loss have been developed, primarily for application to agricultural land. After some experimentation with existing equations in which measured or estimated values of the independent variables were used to compute predicted values of sediment yield, which were then compared with observed yields, it was decided that the loading functions under development should be modifications of the Universal Soil Loss Equation. This decision seemed reasonable based not only on the wide acceptance, but also on the completeness, ease of use, availability of input parameters, and logical appeal of this equation. Two basic modifications of the Universal Soil Loss Equation were fitted to available data from nine separate sites

where actual construction had occurred, and one additional site that contained simulated construction conditions. One of the modifications -- the "delivery-ratio* approach" -- provided a significantly better fit to the observed data than was given by other modification which involved exponents arbitrarily fitted to the factors in the basic equation. Consequently, the delivery-ratio approach was selected for additional fitting.

Two variations on the delivery-ratio modification were fitted and tested. In one, the delivery ratio-factor consists of a variable "distance from construction site to receptor stream" raised to an arbitrarily-fitted exponent. In the other, the ratio factor is "percent of watershed area exposed by construction," also raised to an arbitrarily fitted exponent. The resulting two equations represent the source loading functions for out-of-stream construction activities -- primarily urban construction and highways.

BACKGROUND

The Universal Soil Loss Equation was developed in the late 1950's to predict soil loss from agricultural areas. Its general form is:

$$A = R K L S C P \quad (1)$$

- A is the computed soil loss in tons/acre.
- R is the rainfall factor, designed to account for storm energy and intensity.
- K is the soil erodibility factor, expressing the sediment loss from a specific soil on a unit plot 72.6 feet long with a 9% slope adjusted for rainfall.
- L is the slope-length factor, the ratio of soil loss from a specific slope to that from a 72.6-foot slope of similar characteristics.
- S is the slope steepness factor relating soil loss from a specific slope to that from a 9% slope.
- C is the cropping management factor, a ratio of soil loss from a field under one set of conditions to that from a field under fallow conditions.
- P is the erosion-control practice factor and compares the soil loss from contouring, strip cropping or other structural control methods to that of up-and-down slope, straight-row farming.

The development and evaluation of these factors is discussed in detail by (Wischmeier, 1965, 1971) and (Hotes, 1973). In addition, (Meyer, 1971) reports a very close comparison between a prediction by the Universal Soil Loss Equation for a given subsoil and the average of observed

*The ratio of the amount of sediment that reaches a stream to the amount that was eroded from the construction site.

sediment losses under simulated rainfall from experimental plots shaped to simulate conditions in a construction area.

This equation predicts the amount of soil lost or eroded from its original position and moved to the bottom of the slope, but does not account for any changes in the sediment load that may occur while it is moving toward the stream. These changes are usually in the form of deposition between the bottom of the slope and the receiving stream and can be caused by many factors, including the distance between the construction site and the receptor stream and the character of the intervening terrain--its roughness, cover, slope and shape.

Several investigators have undertaken to develop "delivery ratios." (Roehl, 1962; Williams, 1972; Meyer, 1971). The variables most often used are distance, slope, and total basin area. Of these, some combination of slope and distance appears to be the most promising, as the distance may be broken down into segments and the slope of each combined to account for any irregularity that may be present (Williams, 1972). Most of the work that has been done in this area applies to total watersheds rather than small segments of them. Their accuracy in such situations has not been demonstrated. (Guy, 1972) notes that there are few if any data by which a delivery ratio can be evaluated for small, rapidly changing basins undergoing development.

AVAILABLE DATA

There is a serious lack of field-measurement data on sediment loss and related factors for construction sites. It must be recognized that none of the studies reported in the literature were specifically designed to supply data for developing a construction related loading function. In fact, out of some 500 sources examined, only eight contained sufficient information for this analysis. Even so, many approximations of missing or inadequately defined data had to be made.

The study sites selected were located in several areas of the country, but do not represent a cross-section of all conditions: four are in the Piedmont of Maryland and Virginia; two are in the Southern Piedmont--Georgia and North Carolina; one is in the mountains of central Pennsylvania; and the last is near San Francisco Bay in California.

Since the loading functions under development were closely related to the Universal Soil Loss Equation, it was highly desirable that the cause studies include data that would permit evaluation of the factors in this equation. Also, since the loading functions would probably involve a "delivery-ratio" factor based on distance between disturbed area and receiving stream or on percent of watershed disturbed, it was desirable to have measurements of these factors also. In sum, the desired variables are:

- sediment
- rainfall data
- soil type
- slope gradient of disturbed area
- slope length of disturbed area
- surface condition of disturbed surface
- type of erosion control measures (if any)
- distance of disturbed area from receiving stream
- percent of watershed disturbed by construction,

None of the available data sources included all of these variables, although it was possible to estimate some of the missing data from maps, site layout sketches, and general engineering knowledge of the type of construction.

Exhibit 1 shows the variables measured and reported in the eight case studies used to develop the loading functions, those obtained from other sources, and those estimated from site layouts or derived engineering judgment. Most of the needed data were either provided by the author or obtained from reliable sources such as weather records or Soil Conservation Service soil maps. In only one study, Discker/Cartersville, Georgia, was all of the needed data reported, but this was a small experimental situation although located on an actual construction site.

LOADING FUNCTION

Several models were tested as potential loading functions. These included established soil loss equations such as the Musgrave and the Universal Soil Loss Equation, as well as some arbitrary functions proposed by the investigators. The latter were of the general form of the Musgrave Equation (Musgrave, 1947): multiplicative factors raised to powers, but modified to include additive constants. From the standpoint of estimating observed sediment yields, the Universal Soil Loss Equation proved generally superior to the other forms tested, to the extent that the investigators decided to concentrate on modifying this basic equation to improve its fit to construction-related data. Two types of modifications were evaluated.

In one modification the C and P values (cropping and erosion control factors) were set to unity, a distance factor, D (average distance of overland travel from construction area to receptor stream) was added, and empirically-determined exponents were fitted to the three terrain-related factors to produce a new equation of the form:

$$Y = RKL^a S^b D^c \quad (2)$$

where Y is sediment yield in tons/acre and the other factors are the same as those in the universal and Musgrave equations. With its slope and slope length factors in exponential form, this equation appears to

EXHIBIT 1. DATA FROM CASE STUDIES AND OTHER SOURCES

	Lutes Run (Md)	Bell Pre Creek (Md)	Manor Run (Md)	Yorke & Davis (1972) Rock Creek Study	Vice, Guy, Ferguson (1973) Scott Run (Va)	Guy (1963) Kensington (Md)	Guy (1973) Storm Agnes (Reaton, Va)	Reed (1971) Harrisburg (Pa)	Discher & Richardson (1962) Reader (1973) I-40 (N.C.)	Kott (1973) Colma Creek (Ca)
Sediment yield	X	X	X	X	X	X	X	X	X	X
Rainfall	X+(1)	X+(1)	X+(1)	(2)	(2)	X	(2)	X+(2)	(2)	X+(2)
Soil type	(3)	(3)	(3)	(5)	(3)	(5)	(4)	X	X	(8)
Slope steepness	0	0	0	0	0	0	0	X	0	0
Slope length	0	0	0	0	0	(6)	(6)	X	(6)	0
Surface condition	*	*	*	*	*	X	X	X	X	*
Control measures	X	X	X	*	*	X	X	X	X	*
Distance to stream	(7)	(7)	(7)	(7)	(7)	(6)	(6)	X	N A	(6)
Percent disturbed	X	X	X	X	X	X	X	X	X	X

- X = Given by author of referenced source
- (1) = Supplemented by raw data obtained from author
- (2) = US Weather Bureau TP 40 and Wischmeier rainfall distribution
- (3) = USDA Soil Conservation Service (SCS), Montgomery County, Md., Office
- (4) = SCS, Harrisburg, Pa.
- (5) = SCS, Fairfax Co., Va.
- (6) = Estimated from site map/diagram
- (7) = Estimated from SCS maps
- (8) = Estimated by MITRE after consultation with SCS San Francisco office and comparison with other California soil data
- N A = Not applicable; measurement taken at end of experimental plot
- * = When not stated by author, surface condition was assumed to be raw cut or dense compaction with no control measure
- 0 = Estimated by MITRE from engineering judgement based on type of construction in given terrain

provide the flexibility needed for adaptation to construction conditions. However, when the exponents were fitted to observed data by the method of least squares, the resulting function gave predicted yields that compared less closely with observed yields than did the predictions of the Universal Soil Loss Equation. This result is ambiguous at best, since the above equation with three arbitrarily-fitted constants should theoretically have given at least as close a fit as the deterministic Universal Soil Loss Equation. This difference was attributed to sparse data of unknown reliability, and the above equation was abandoned in favor of a simpler formulation bearing a closer relation to the Universal Soil Loss Equation.

The second modification was a simpler model utilizing the basic Universal Soil Loss Equation adjusted by a "delivery ratio." While the concept of a delivery-ratio has been suggested and applied by several investigators, (Roehl, 1962; Williams, 1972; Meyer, 1971), the forms of this factor used in the present study and their application to construction-site data have not to our knowledge previously been investigated.

Two intuitively relevant parameters that could be evaluated for most of the case studies were chosen as the variable in the delivery-ratio. These parameters are D, the distance between construction site and receptor stream in feet; and %A, the percent of drainage basin exposed by construction. The method of least squares was used to determine appropriate exponents for these two parameters.

The resulting functions were obtained:

$$Y = R K L S C P D^{-0.22} \quad (3)$$

$$Y = R K L S C P (\%A)^{-0.51} \quad (4)$$

These two equations were considered by the investigators to be the best sediment loading functions readily obtainable from the available data.

RESULTS

Sample results obtained by applying these loading functions to data from one study is presented in Exhibit 2. Sediment yield rates obtained from each function are expressed as ratios to the observed rates. To facilitate comparison, these ratios are displayed together with the prediction obtained from the Universal Soil Loss Equation and with values of certain critical parameters that enter into the yield calculations.

The improvement in predictive capability of the two fitted loading functions relative to the Universal Equation for construction sites is indicated by the generally lower values of the predicted/observed ratio values for the loading functions. The average values over all case studies are as follows:

EXHIBIT 2. COMPARISON OF FITTED FUNCTIONS FOR A REPRESENTATIVE DATA SET

Case, Location and Date	Watershed Area	% Area Disturbed by Constr	Distance to receptor stream	Yield (Observed)	By Universal Soil Loss Equation		By Loading Function Adjusted For Distance to Stream		By Loading Function Adjusted For % Area Disturbed	
					Yield (Predicted)	Ratio Predicted/ Observed	Yield (Predicted)	Ratio Predicted/ Observed	Yield (Predicted)	Ratio Predicted/ Observed
	acres		feet	tons/acre	tons/acre		tons/acre		tons/acre	
(3-13) Yorke & Davis Rock Creek- Anacostia										
<u>Lutes Run</u>										
7/20/67	301	9.6	300	2.5	11.7	4.6	3.3	1.3	3.6	1.45
8/19/67		9.6		1.18	6.95	5.9	2.0	1.7	2.2	1.86
10/25/67		8.3		1.28	9.48	7.4	2.7	2.1	3.2	2.5
3/17/68				2.31	1.69	0.73	0.5	0.21	0.8	0.34
5/27/68				2.31	3.69	1.6	1.1	0.46	1.8	0.76
7/02/68				4.08	13.23	3.2	3.8	0.92	6.2	1.52
<u>Bel Pre Creek</u>										
11/28/66	1082	13.9	400	0.36	1.71	4.7	0.47	1.3	0.44	1.23
5/07/67		13.8		1.11	4.15	3.7	1.1	0.99	1.1	0.97
7/20/67		13.6		0.39	1.24	3.2	0.33	0.85	0.33	0.85
8/03/67		13.4		3.58	8.82	2.5	2.4	0.66	2.4	0.67
8/24-25/67		13.4		3.07	8.29	2.7	2.2	0.72	2.2	0.72
6/19-20/68		9.7		1.00	4.98	5.0	1.3	1.34	1.6	1.57
7/2-3/68		9.7		0.50	4.32	8.6	1.2	2.3	1.4	2.7
<u>Manor Run</u>										
11/28/66	646	8.0	300	0.25	2.51	10.2	0.73	2.9	0.88	3.53
5/07/67		10.8		3.8	6.10	1.6	1.7	0.46	1.7	0.46
8/03/67		11.0		6.15	12.96	2.1	4.9	0.80	3.8	0.62
8/24-25/67		11.0		19.44	12.18	0.63	3.5	0.18	3.7	0.19
6/19-20/68		11.8		6.49	7.38	1.1	2.0	0.31	2.0	0.31
7/2-3/68		11.8		3.04	6.36	2.1	1.8	0.60	1.8	0.60

Average Value of
Predicted/Observed Ratio

Universal Soil Loss Equation	7.37
Loading function with adjustment for distance	1.33
Loading function with adjustment for percent of watershed area disturbed	1.78

The above values are averages of ratios of predicted (or estimated) yields in tons/acre to observed yields in the same unit. Thus a ratio of 1.00 indicates that the calculated and observed values are equal.

The method used to compare the loading functions with each other and with the Universal Soil Loss Equation does not readily lend itself to statistical analysis. Predicted yields less than the corresponding observed yield produces a ratio value between zero and unity, but never negative; and any estimate greater than the observed yield produces a value greater than unity — sometimes much greater since it is not constrained by an upper bound as in the case of the less-than-observed ratio. If, for example, an estimated value is one-fifth the observed, the ratio is 0.20. If it is five times greater, the value is 5.00. The average of these two ratio values is 2.60, implying that "on the average" the predicted values are 2.6 times greater than observed. From one standpoint, the average appears unduly weighted by the large ratio values when the estimate exceeds the observed value. This weighting effect is similarly reflected in measures of scatter such as the range or standard deviation.

With the above observations and caveats, the summary statistics of the yield ratios for values predicted by the Universal Soil Loss Equation and the two loading functions are given in Exhibit 3. In presenting

Exhibit 3. MEANS AND STANDARD DEVIATIONS OF PREDICTED/OBSERVED
RATIOS OBTAINED BY THREE ESTIMATING PROCEDURES

	By Universal Soil Loss Equation	By Loading Function Adjusted for Distance to Stream	By Loading Function Adjusted for % Area Disturbed
Average of All Ratio Values*	7.37	1.33	1.78
Standard Deviations	11.20	2.23	3.09
Number of Observations* in above statistics	53	47	53

these results, the authors emphasize that the statistics have not been subjected to a thorough evaluation and therefore are not recommended for use in testing of hypotheses concerning closeness of fit of predicted-to-observed yields or of similarity among results predicted by the three methods.

Perhaps more revealing and more easily interpreted than the summary statistics are the frequency distributions of ratios presented in Exhibit 4. As expected, the predictions by the Universal Soil Loss Equation tend generally to overestimate the sediment yield, because the effects of terrain between disturbed area and point of measurement are not considered.

The frequency distribution for the loading function adjusted for distance between disturbed area and receptor stream exhibits a definite clustering near the ratio value of 1.00, and shows a general symmetry about this value. In this distribution, approximately 53 percent of the yield ratios lie between values of 0.50 and 1.50, implying that 53 percent of the estimated yields fell within ± 50 percent of the observed. Also, about 90 percent of the values lie between 0.20 and 5.00, implying that 90 percent of the estimated yields fall within one-fifth and five times the observed value. The median lies in the interval 0.67-1.00. These percentage intervals and ranges are based on the limited data available for this report, and should not be considered universally applicable.

The function adjusted for percent of basin area disturbed by construction also exhibits a clustering about the ratio value of 1.0. The distribution appears generally symmetric about this value. Some 30 percent of the estimated values fall within ± 50 percent of the observed values. Also, about 84 percent of the ratios lie between 0.20 and 5.00. The median lies between ratio values of 1.01 and 1.50.

LIMITATIONS

There are several conditions to consider before using these functions.

- o The potential user should recognize that the soil type, terrain, and rainfall patterns of the case study sites were not fully representative of the United States. In particular, the Great Plains and Western Mountain areas were not included.
- o The functions were developed from available data from the literature rather than from experiments designed specifically for this purpose, and the results did not lend themselves readily to straightforward statistical analysis. The level of analysis performed thus far has not been sufficiently detailed to permit testing of hypotheses or setting confidence limits on the accuracy of estimates.
- o The Universal Soil Loss Equation was designed for agricultural uses east of the Rocky Mountains, addressing generally long, regular, gentle slopes. Construction sites are usually far from regular and may include steep highway banks, internally drained excavations and other irregular features that are constantly changing shape as construction progresses. The

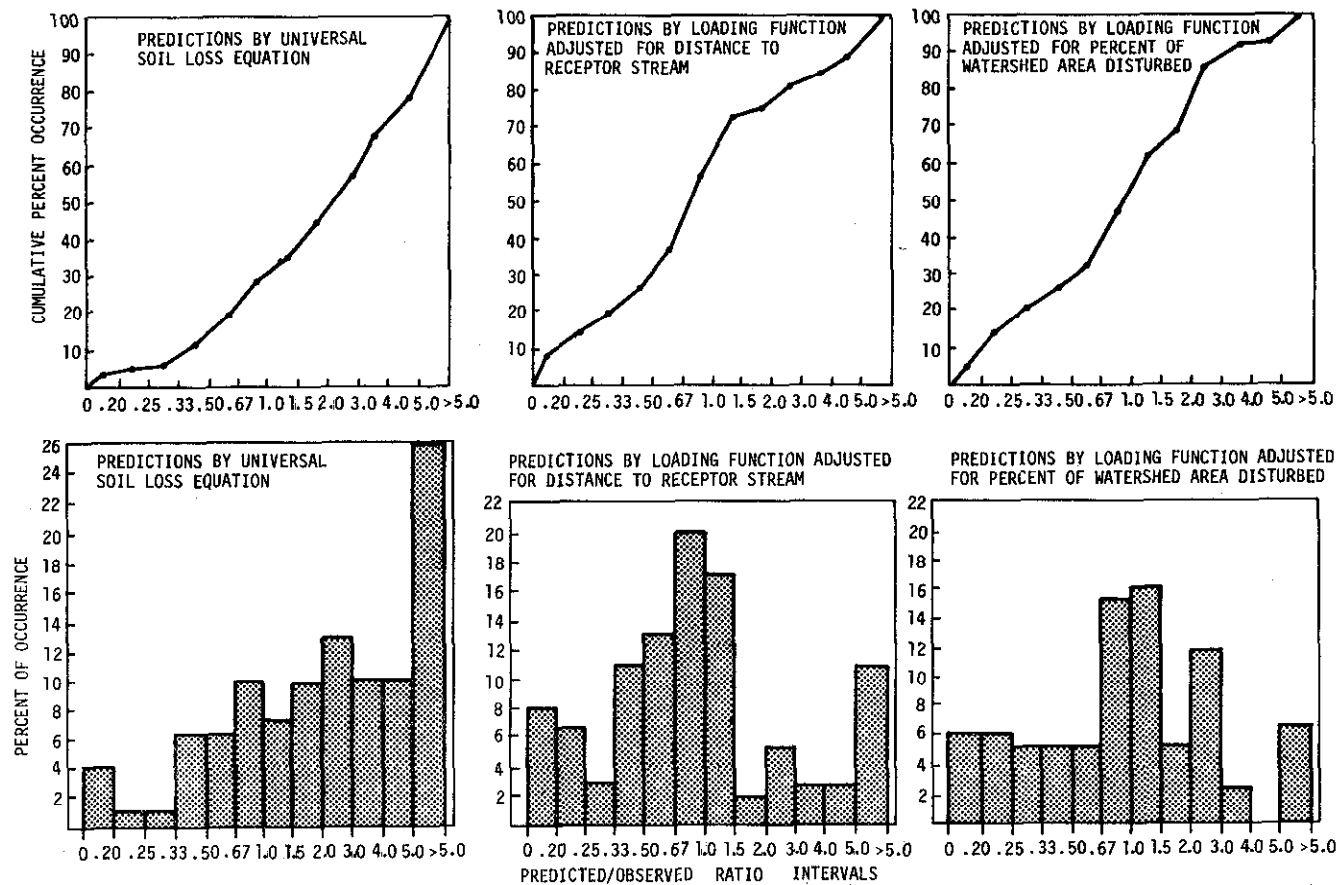


EXHIBIT 4
PERCENT FREQUENCY DISTRIBUTIONS PREDICTED/OBSERVED RATIOS

determination of the best composite LS (length/steepness) term for a given construction area requires much effort in following and weighting the changes in various eroding and depositional segments of the exposed area.

- o Mixing of different soils, or of topsoils and subsoils, and differential compaction pose difficult problems when using K values determined for the soils in their natural states.
- o The rainfall erosion index, R, is based on long-term averages. Therefore, the shorter the time period during which construction activities expose the soil, the more likely that non-average rainfall will occur, allowing the possibility of large errors in the soil loss prediction. Questions also exist about its applicability to the West Coast and about the effects of variations in the yearly distribution of rain.

In spite of the above difficulties, few if any models for predicting sediment yield from construction sites have been examined and analyzed to the extent of the loading functions developed in this report. The superiority of these loading functions to the Universal Soil Loss Equation for computing sediment reaching a watercourse some distance from the disturbed area seems intuitively apparent (although not statistically proven) from the frequency distributions in Exhibit 4.

In summary, the authors conclude that the loading functions developed here provide the best available means for predicting the sediment yield from a construction site, in the absence of specific yield data for that site. This conclusion is based on an extensive review of the literature as well as the foregoing analysis of data. Although no solid statistical basis has been developed for assessing the accuracy of their estimates, some general indications of the relation of estimated yields to observed yields may be drawn from the frequency distributions of Exhibit 4.

Regarding the choice of which loading function should be used, visual comparison of the frequency diagrams in Exhibit 4 suggests that the distance-to-stream adjustment provides a somewhat better agreement between estimated and observed values, but this difference is sufficiently slight to be viewed as insignificant. The user could base his choice on whether distance-to-stream data or disturbed-area data are more readily available. When both are available, the authors recommend that the function involving distance-to-stream be used since this function gave a slightly better fit of estimated to observed soil losses.

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VARIATION AND CAUSATIVE FACTORS OF SEDIMENT YIELDS IN THE ARKANSAS RIVER BASIN, KANSAS

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ABSTRACT

Measured sediment yields in the Arkansas River basin of Kansas range from about 10 to 500 tonnes per year per square kilometre (30 to 1,430 tons per year per square mile); highest yields occur in the eastern third of the basin and low yields occur in various parts of the western two-thirds. Yields predicted from general curves based on climate (Schumm, 1965) agree poorly with measured yields. To improve the correlation between calculated (predicted) and measured yields, the climate-dependent curves are converted to a single curve dependent on runoff that is more directly applicable to sediment yield. The yields predicted by this curve for specific areas are adjusted by applying a power function of average slope. Where other determinants of sediment discharge do not increase or decrease yields significantly, adjusted yields show rough agreement with those measured. Discrepancies between the calculated and measured yields generally are inferred to be a result of geologic influences. Calculation of the adjusted yields permits a refined delineation of areal variations in sediment yields based on sample data, and provides a means of estimating yields from unsampled basins.

INTRODUCTION

The Arkansas River basin of Kansas occupies much of the southern half of the State. Physical features in the basin differ markedly from west to east, but it is an area in which urbanization, hydraulic structures, and possibly land use have minor influences on sediment yields as compared to other large basins of the central United States. Suspended-sediment data from the basin are sufficient to roughly define areal variations in sediment yields, as well as to identify at least qualitatively, the relative importance of the major determinants of sediment yield. An initial assumption of this study is that those determinants are climate, geology and soils, vegetation, topography, and the effects of man.

The purpose of this study is to define and explain sediment-yield variations resulting principally from natural factors, but including the typical man-imposed stresses of grazing, agriculture, and a rural population. Truly natural conditions occur virtually nowhere in southern Kansas. Sediment data from several drainage basins of southern Kansas, particularly in the eastern part, probably are influenced significantly by dam construction or land-use activities, and therefore, are not included.

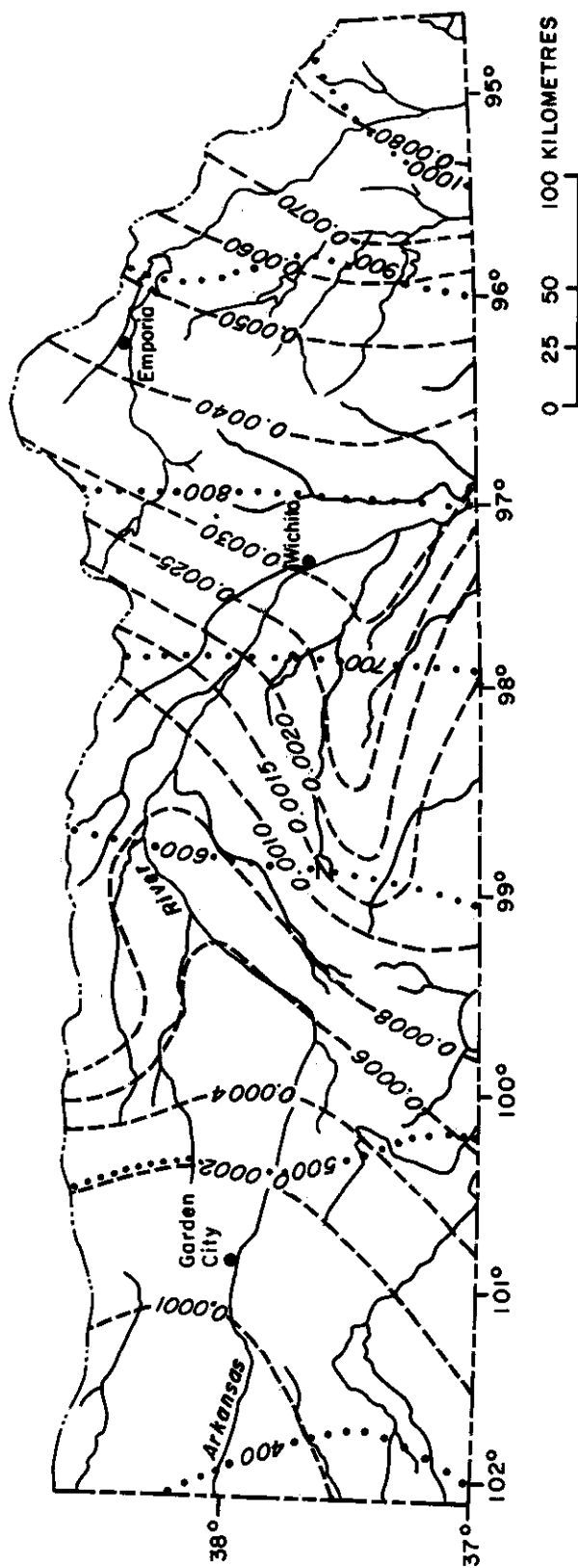


Figure 1.--Average annual precipitation, in millimetres (dotted lines), and average runoff, in cubic metres per square kilometre (dashed lines), in the Arkansas River basin, Kansas.

Average annual precipitation steadily increases across the Arkansas River basin of Kansas from about 380 mm (15 in) in the west to about 1,040 mm (41 in) in the southeastern corner (fig. 1). Runoff increases in a similar though less regular manner (fig. 1). Temperatures show large seasonal variation, but the average annual temperature everywhere in southern Kansas is 13°C (55°F) $\pm 2^{\circ}\text{C}$ (4°F). Vegetation is strongly influenced by agriculture and, of course, climate. Relatively natural vegetation covers about a third of the basin and is dominated by prairie grasses.

The physiographic divisions of the Arkansas River basin of Kansas (fig. 2) result from differences in topography and geology. The High Plains have very gentle slopes predominantly on a surface of loess. Westward and northward extension of stream channels into the High Plains has caused moderate relief and exposure of shale and limestone of Cretaceous age in the Dissected High Plains, and exposure of shale, siltstone, and sandstone of Permian age in the Red Hills. Stable sand dunes cover a large area of the Arkansas River Lowlands between the dissected areas and locally in the southwest corner of the State. Elsewhere sandy alluvium dominates the surface of the lowlands. The eastern third of the basin largely is underlain by gently westward-dipping interbedded shale and limestone. Dissection of the beds has formed moderate slopes, particularly in the Flint Hills Upland where the limestones of Permian age contain resistant chert. The limestones of Pennsylvanian age in the Osage Cuestas form a less rugged but similar topography. The Cherokee Lowland is a very gently rolling erosional plain underlain by sandstone and shale of Pennsylvanian age.

The climatic and vegetative differences across southern Kansas are gradational, but the topographic and surficial geologic variations generally are easily separable. This condition allows easy comparison of sediment data collected from the various parts of the basin.

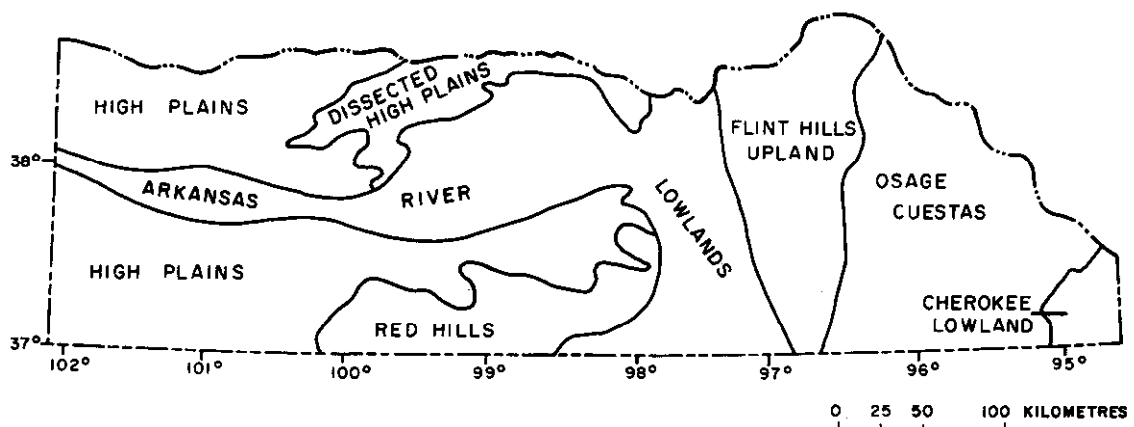


Figure 2.--Physiographic divisions of the Arkansas River basin, Kansas (after Schoewe, 1949).

MEASURED SEDIMENT YIELDS

Suspended-sediment data from 4 daily stations and 29 periodic (less frequent than daily) stations were used to calculate suspended-sediment yields per unit time and area for drainage basins wholly or partly in southern Kansas (table 1). Yields at daily stations were calculated directly from published sediment data; yields from the periodic data were calculated using standard techniques in which a sediment-rating curve and flow-duration curve are combined. Most of the rating curves are well defined, and many of the results for periodic stations are considered as reliable as those from daily records (table 1). Using published data for Kansas streams (Albert, 1969), suspended loads were converted to total loads.

The sediment-sample data indicate that yields are highest in the Flint Hills (figs. 2 and 3), averaging nearly $200 \text{ tonnes}\cdot\text{yr}^{-1}\cdot\text{km}^{-2}$ ($570 \text{ tons}\cdot\text{yr}^{-1}\cdot\text{mi}^{-2}$) and locally reaching nearly $500 \text{ tonnes}\cdot\text{yr}^{-1}\cdot\text{km}^{-2}$ ($1,430 \text{ tons}\cdot\text{yr}^{-1}\cdot\text{mi}^{-2}$). Eastward, yields decrease to about $100 \text{ tonnes}\cdot\text{yr}^{-1}\cdot\text{km}^{-2}$ ($290 \text{ tons}\cdot\text{yr}^{-1}\cdot\text{mi}^{-2}$) in the Osage Cuestas. Reliable data are not available from the Cherokee Lowland. West of the Flint Hills, yields reach about $100 \text{ tonnes}\cdot\text{yr}^{-1}\cdot\text{km}^{-2}$ ($310 \text{ tons}\cdot\text{yr}^{-1}\cdot\text{mi}^{-2}$) in the Red Hills and adjacent parts of the Arkansas River Lowlands. Elsewhere yields generally are relatively low: about $20 \text{ tonnes}\cdot\text{yr}^{-1}\cdot\text{km}^{-2}$ ($60 \text{ tons}\cdot\text{yr}^{-1}\cdot\text{mi}^{-2}$) in the High Plains and dune-sand areas, $50 \text{ tonnes}\cdot\text{yr}^{-1}\cdot\text{km}^{-2}$ ($140 \text{ tons}\cdot\text{yr}^{-1}\cdot\text{mi}^{-2}$) on the Dissected High Plains, and possibly $10 \text{ tonnes}\cdot\text{yr}^{-1}\cdot\text{km}^{-2}$ ($30 \text{ tons}\cdot\text{yr}^{-1}\cdot\text{mi}^{-2}$) along much of the Arkansas River Lowlands. The most notable exception is the Cimarron River in southwest Kansas, where a yield of $192 \text{ tonnes}\cdot\text{yr}^{-1}\cdot\text{km}^{-2}$ ($549 \text{ tons}\cdot\text{yr}^{-1}\cdot\text{mi}^{-2}$) was calculated.

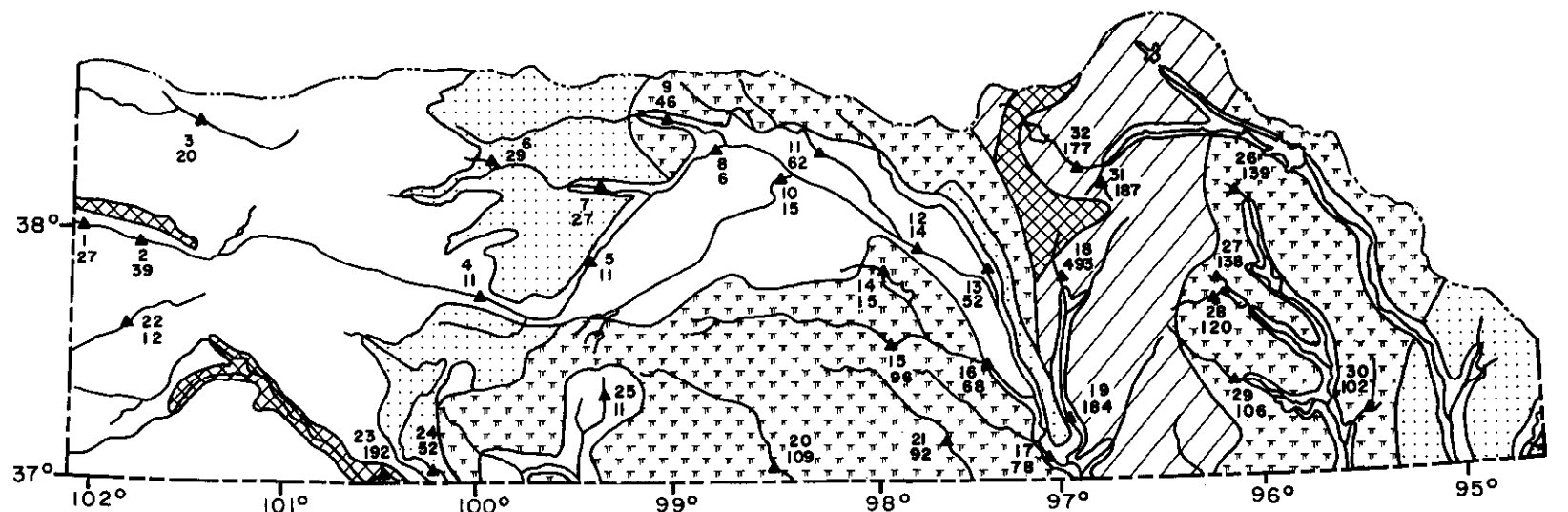
CLIMATIC EFFECTS ON SEDIMENT YIELDS

The sediment-yield zones of figure 3 were determined by interpolation of the measured yields on the basis of physical controls, the first considered being climate. Schumm (1965) shows that for the conterminous United States, sediment yields are a function of both average annual precipitation and average annual temperature. He presents curves showing that sediment yields are highest at precipitation rates great enough to produce significant runoff and low enough that vegetation is fragile and ineffective to control erosion. Owing to evapotranspiration, the sediment-yield peaks are temperature dependent, a higher amount of precipitation being necessary to support vegetation with increase of temperature (fig. 4).

Table 1.--Sediment-sampling sites, Arkansas River basin, Kansas.

Map No. <u>a/</u>	Station Name	Sampling Frequency	Esti- mated Relia- bility of Re- sults	Sedi- ment Yield [tonnes· yr ⁻¹ ·km ⁻²]
1	Arkansas River near Coolidge, Ks.	Monthly	Poor	27
2	Arkansas River at Syracuse, Ks.	Monthly	Fair	39
3	Whitewoman Creek near Leoti, Ks.	Infrequent	Poor	20
4	Arkansas River at Dodge City, Ks.	Monthly	Good	11
5	Arkansas River near Kinsley, Ks.	Daily	Good	11
6	Guzzlers Gulch near Ness City, Ks.	Infrequent	Poor	29
7	Pawnee River near Larned, Ks.	Monthly	Fair	27
8	Arkansas River at Great Bend, Ks.	Monthly	Fair	6
9	Walnut Creek at Albert, Ks.	Monthly	Fair	46
10	Rattlesnake Creek near Raymond, Ks.	Infrequent	Poor	15
11	Cow Creek near Lyons, Ks.	Monthly	Good	62
12	Arkansas River near Hutchinson, Ks.	Daily	Good	14
13	Little Arkansas River at Valley Center, Ks.	Monthly	Fair	52
14	N. F. Ninnescah River above Cheney Res., Ks.	Monthly	Good	15
15	S. F. Ninnescah River near Murdock, Ks.	Monthly	Good	96
16	Ninnescah River near Peck, Ks.	Monthly	Fair	68
17	Arkansas River at Arkansas City, Ks.	Monthly	Good	78
18	Whitewater River at Towanda, Ks.	Monthly	Good	493
19	Walnut River at Winfield, Ks.	Daily	Good	184
20	Medicine Lodge River near Kiowa, Ks.	Infrequent	Fair	109
21	Chikaskia River near Corbin, Ks.	Daily	Poor	92
22	Bear Creek near Johnson, Ks.	Infrequent	Poor	12
23	Cimarron River near Forgan, Okla.	Infrequent	Poor	192
24	Crooked Creek near Nye, Ks.	Infrequent	Fair	52
25	Cavalry Creek at Coldwater, Ks.	Monthly	Fair	11
26	Verdigris River near Madison, Ks.	Weekly	Good	139
27	Fall River near Eureka, Ks.	Monthly	Good	138
28	Otter Creek at Climax, Ks.	Monthly	Good	120
29	Elk River at Elk Falls, Ks.	Monthly	Good	116
30	Big Hill Creek near Cherryvale, Ks.	Monthly	Good	102
	Little Caney River near Copan, Okla. <u>b/</u>	Monthly	Fair	74
31	Cedar Creek near Cedar Point, Ks.	Monthly	Good	187
32	Cottonwood River near Plymouth, Ks.	Monthly	Good	177

a/ Map numbers refer to figure 3; b/ not shown on figure.



EXPLANATION

Areas of inferred range in sediment yield,
in tonnes per year per square kilometre



0-40



40-80



80-140



140-200



More than 200



Sediment-sampling
site

Top number is map number (table 1); lower
number gives sediment yield in tonnes·yr⁻¹·km⁻²
determined from samples

0 25 50 100 KILOMETRES

Figure 3.--Variation of sediment yields in the Arkansas River basin, Kansas.

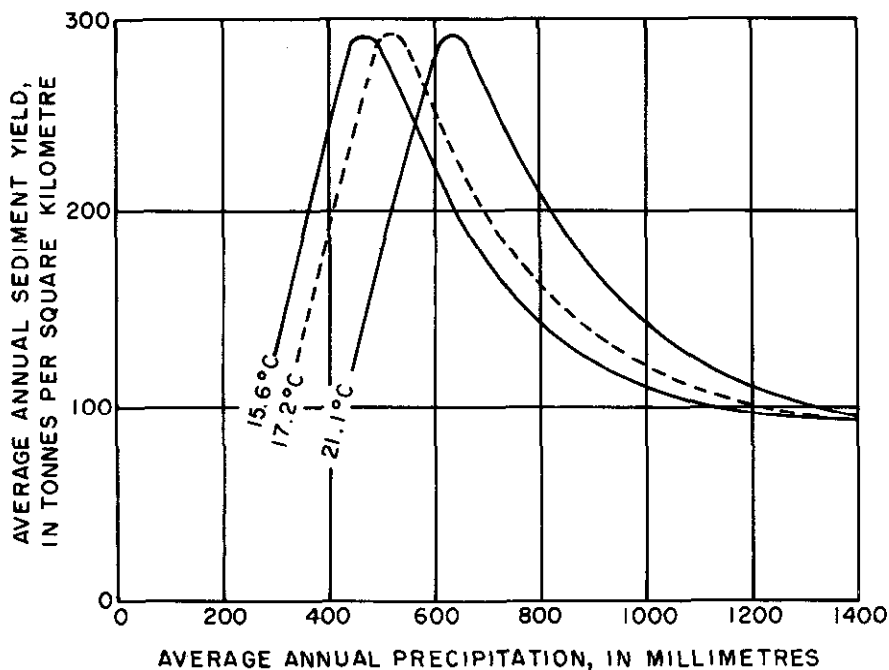


Figure 4.--Variations of sediment yield with average annual precipitation (after Schumm, 1965).

In southern Kansas, about three-fourths of the precipitation falls during the warmest 6 months. Thus, the effective average temperature is higher than the average annual temperature. To determine an effective temperature, corresponding precipitation and runoff data (fig. 1) were plotted and compared to curves drawn by Langbein et. al. (1949) for the conterminous United States (fig. 5). The graph shows that the effective average temperature of southern Kansas is slightly higher than 17°C (63°F) except in the extreme eastern part, where it is slightly lower. Thus a 17.2°C (63°F) curve is included with the sediment-yield curves of Schumm (1965) (fig. 4).

Estimates of sediment yield based on precipitation and temperature, however, are necessarily inaccurate. Runoff is a better index of fluvial-sediment transport because runoff depends on precipitation and temperature as well as other variables including seasonal distribution of precipitation, intensities and durations of storms, land-use patterns, and geology. For this reason, and largely to eliminate temperature dependence, the curve for 17.2°C (63°F) (fig. 4) was combined with the runoff-precipitation curve for southern Kansas (fig. 5), to produce an idealized curve relating the runoff rates to sediment-yield values for the United States in general (fig. 6). This idealized curve accounts for the effects of climate and vegetation, and predicts the sediment

yields that should occur in southern Kansas at various runoff rates if it is assumed that other major controls--geology, topography, and land use--are constant and typical of the United States. Significant deviation of measured yields from the ideal curve is indication that the assumption is invalid. Moreover, geology and topography become isolated as the causes for deviation because the sampled streams (table 1) were selected on the basis of minimal human activity.

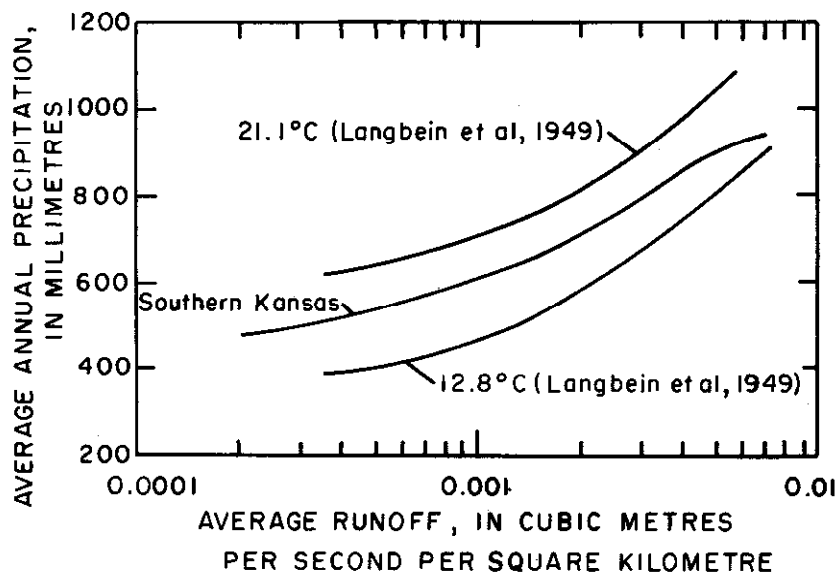


Figure 5.--Variations of runoff with average annual precipitation.

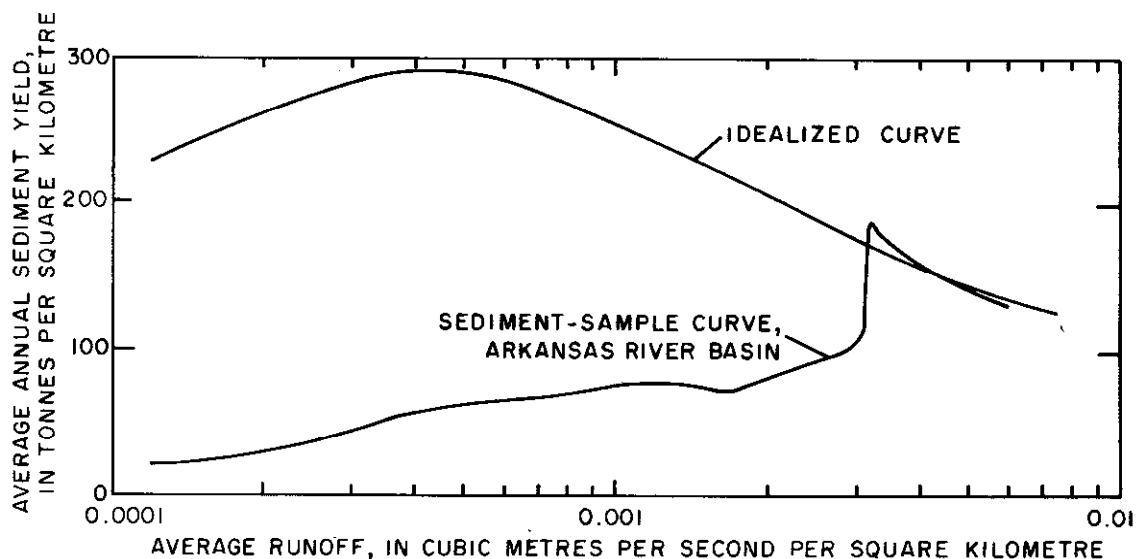


Figure 6.--Variations of sediment yield with runoff in the Arkansas River basin, Kansas.

The extent to which measured sediment yields of the Arkansas River basin of Kansas differ from the predicted yields at prevailing runoff rates is generalized in figure 6. In the Flint Hills and Osage Cuestas, where runoff exceeds $0.003 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{km}^{-2}$ (about $0.3 \text{ ft}^3 \cdot \text{s}^{-1} \cdot \text{mi}^{-2}$), the measured and predicted sediment yields are similar. For lower runoff rates, however, measured yields average about a third of the predicted amounts. These rates prevail in the western two-thirds of southern Kansas, which contrasts sharply with most of the eastern third in surficial geology and topography.

ADJUSTMENT FOR AVERAGE SLOPE

To explain the variations of sediment yield for southern Kansas and the deviation of measured yields from those predicted, and to establish areal applicability of the measured yields (table 1, fig. 3), topography is considered by using the average slope. The sediment yield-precipitation curves (fig. 4) are based on drainage basins of about $3,900 \text{ km}^2$ ($1,500 \text{ mi}^2$) (Schumm, 1965). Selection of a limited range of sizes was necessary because average slope tends to decrease with increase in basin area, and sediment yields generally increase with increase in average slope. Thus, the curves of Schumm (1965) relating sediment yields to climate implicitly are based on an average but unknown slope, and the appropriate curve applies to any drainage basin of the same average slope, regardless of size. Conversely, the curves do not apply to basins of different average slope, regardless of size. An adjustment based on average slope of sediment yields as predicted by the idealized curve (fig. 6), and comparison of the adjusted results with measured yields, therefore, can provide (1) a basis for evaluating the reliability of sample data, (2) a method of separating the effects of topography from those of geology, and (3) a method to expand the utility of measured yields or to calculate yields for basins from which sediment data are not available.

The adjustment proposed here is founded on soil-loss studies of croplands and assumes that sediment yields vary with the 1.35 power of the slope (Musgrave, 1947). Owing largely to best-fit attempts, it further is assumed that the typical slope upon which the curves of Schumm (1965) and the idealized runoff curve (fig. 6) are based is 5.3 percent. An adjustment then can be made if average slope and runoff for the basin or area are known. From the idealized curve (fig. 6), an average annual sediment yield, Y_i is determined for the known runoff and assumed average slope of 5.3 percent. If the actual average slope is S and adjusted yield is Y_a , then:

$$\frac{Y_a}{Y_i} = \frac{S^{1.35}}{5.3^{1.35}} \quad (1)$$

and

$$Y_a = \frac{(Y_i) (S^{1.35})}{9.5} \quad (2)$$

In figure 7, adjusted yields calculated for various parts of southern Kansas are compared to measured results for the same areas. Randomly selected points on 72 topographic maps were used for determination of average slope, and runoff values were taken from figure 1. Local variations in yield are great enough that both the adjusted and measured results of figure 7 are simplified and, therefore, interpretive.

Similarity is apparent between adjusted (calculated) and measured yields for the High Plains, Arkansas River Lowlands, and Osage Cuestas (fig. 7). Agreement also seems satisfactory for the Red Hills and sand dunes, but the comparisons for those areas are based on limited sample data. Substantial differences, however, are evident between calculated and measured yields of the Dissected High Plains and Flint Hills Upland. For those areas, geologic influences on sediment yields are possible causes for the discrepancies. For example, measured sediment yields for the western part of the Flint Hills average two to three times higher than calculated yields, regardless of north-south position (fig. 7). West of the Whitewater and Walnut Rivers are exposures of gypsiferous shale, which generally provide highly dispersed and erodable clay (Flaxman, 1966). Relative to the eastern parts of the Flint Hills, the beds are soft and homogeneous, resulting in lower average slopes (Leonard, 1972).

In the Dissected High Plains measured yields are much lower than calculated yields (fig. 7), but the probable cause for the differences is unclear. Contrary to the previous assumption of a geologic influence, low yields in the Dissected High Plains may be caused by terracing, irrigated agriculture, and construction in recent years of numerous small reservoirs rather than by anomalous geologic conditions. Another possibility is short- to intermediate-term changes in the precipitation-runoff relationship, whether natural or induced. Weather records for the last 20 years in western Kansas show that average annual precipitation has remained steady, but average runoff and the occurrences of intense storms have decreased (J. A. Power, written commun., 1975). Low measured yields and aggradation along stream channels owing to reduced flood peaks are possible results of these changes. The specific reasons for yields being lower than predicted are not known, but it seems that factors other than those considered in this paper are affecting fluvial-sediment transport in the Dissected High Plains.

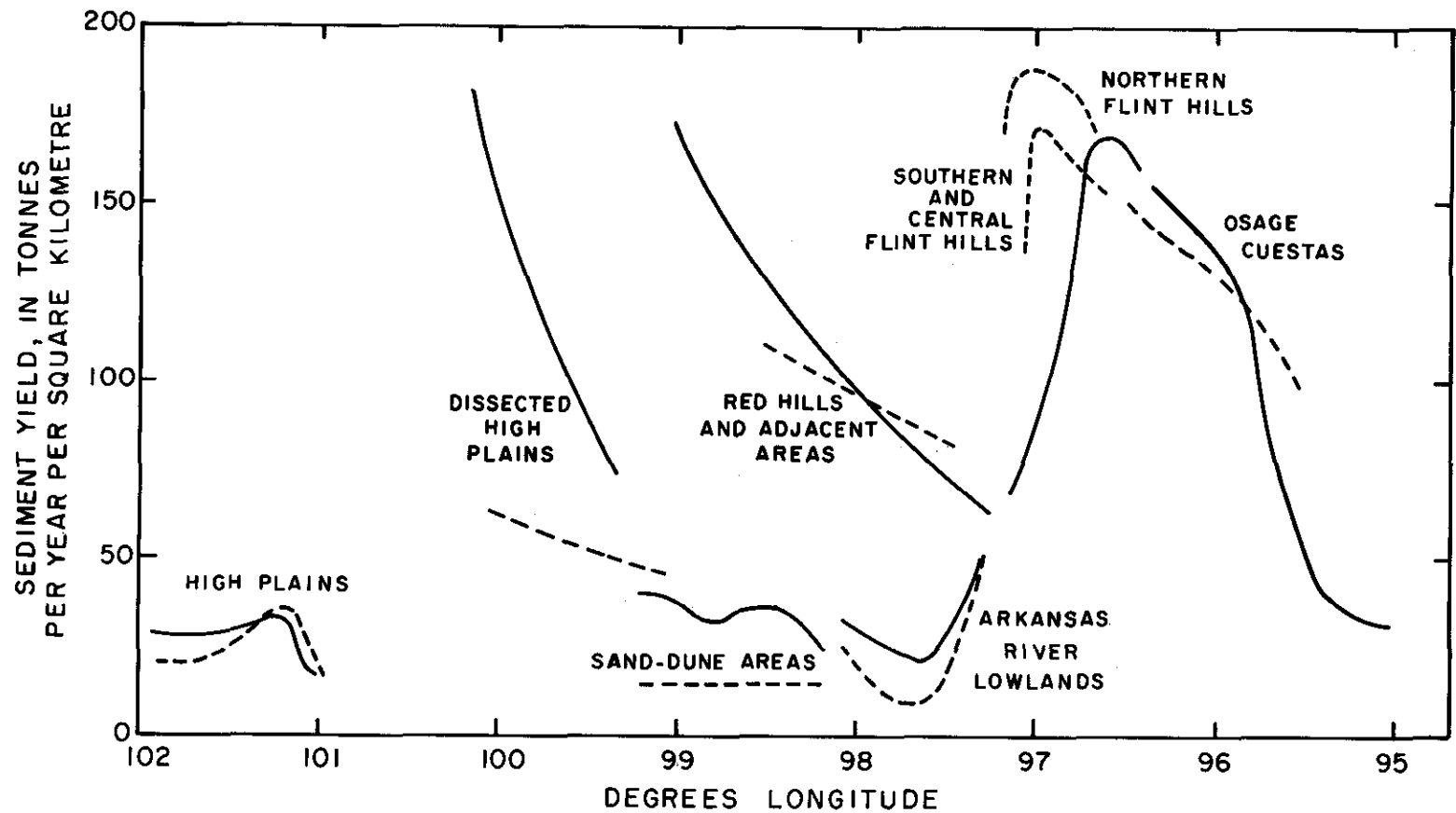


Figure 7.--Comparisons of measured sediment yields (dashed lines) with calculated sediment yields (solid lines) for various parts of the Arkansas River basin, Kansas.

CONCLUSIONS

The sediment-yield map for the Arkansas River basin of Kansas (fig. 3) is based on control points derived from sample data (table 1), but almost all detailed variations on the map result from calculations for yield using only runoff and slope data. The agreement obtained for most areas of the basin between sample and calculated yields suggests that slope and runoff are the two primary natural determinants of sediment discharge. Climate and natural vegetation are of minor consideration because the effects of both are reflected by runoff. Geologic influences on sediment yields, which also are manifested in part by runoff and slope, appear to be important considerations only under unusual conditions.

The limiting assumptions of the method described here for calculating sediment yields are presently the major deficiency of the approach. Further study, however, may suggest ways in which the effects of land use can be quantified and incorporated, and how geology can be treated as other than an anomalous residual. If a basin includes highly dissected loess deposits, for example, further adjustment dependent on the areal extent of the loess might avoid underestimation of yields as now would be the case. Similarly, recognition of the distribution of highly permeable soils, such as those of dune sand, could prevent overestimation of sediment yields.

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SEDIMENT SOURCES AND YIELDS FROM SAGEBRUSH
RANGELAND WATERSHEDS^{1/}

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ABSTRACT

Average sediment yields from the Reynolds Creek Experimental Watershed and three subwatersheds ranged from 1.14 to 1.90 tonnes/ha/year (0.51 to 0.85 tons/ac/year) during the study period. Yields were more than tenfold higher in wet than in dry years and about 90 percent of average yearly yield occurred during January, February, and March at the Reynolds Outlet Station. Sediment yields from six upland source areas, 0.9 to 83 ha (2.25 to 205 acres), was one-third or less per unit area than that from larger downstream watersheds. Bedload transport data collected by use of Helley-Smith bedload samplers showed that bedload averaged about 20 percent of total sediment yield. Analysis of runoff-sediment events by parameter optimization showed excellent correlation between suspended sediment volume and combined peak flow and runoff volume. The procedure should be useful in predicting sediment yields from similar areas having a minimum of sediment data.

INTRODUCTION

Eroded hillslopes, roads, and streambanks; damaged bridges; reservoir sediment deposits; and freshly eroded gullies are visual reminders that erosion and sediment yield from sagebrush rangelands are serious in the Northwestern United States. Yet, few studies are in progress to determine sediment sources, amounts, occurrence frequency, and control methods.

The Reynolds Creek Experimental Watershed in southwest Idaho was selected in 1960 to represent extensive rangeland areas in Idaho and surrounding states in studying the hydrology and sedimentation characteristics of these lands (Robins, et al., 1965). This paper summarizes data from the Reynolds Creek Watershed, three subwatersheds, and six upland source areas to provide information for private landowners, the Bureau of Land Management, U.S.D.I., the Soil Conservation Service, U.S.D.A., and other agencies responsible for management of such lands.

^{1/} Contribution from the Northwest Watershed Research Center, Agricultural Research Service, U.S.D.A., Boise, Idaho; Bureau of Land Management, U.S.D.I.; and Idaho Agricultural Experiment Station, cooperating.

The Reynolds Creek Experimental Watershed

Reynolds Creek is a direct tributary to the Snake River about 24 km (15 mi) upstream from Marsing, Idaho. The experimental watershed outflow station is about 16 km (10 mi) upstream from the confluence with the Snake River and has a drainage area of 23,369 ha (90 mi²). Figure 1 shows elevation contours and locations of rain gage sites, source area stations, and watershed runoff stations. Details of hydrologic instrumentations have been reported (Johnson, et al., 1974a). Average annual precipitation ranges from about 254 mm (10 in) at elevations below 1220 m (4000 ft) to more than 1143 mm (45 in) at elevations near 2227 m (7300 ft). Land is used mainly for cattle grazing except about 3 percent of the area is irrigated hay and feed crops and another 3 percent is forest, mostly Douglas fir and aspen, on protected north slopes. The soils and geology of the area are described in other reports (Hobbs and Burford, 1970; McIntyre, 1972). Vegetative cover ranges from less than 25 percent at low-precipitation and thin-soil sites to nearly 100 percent at highest elevation and deep-soil sites.

Procedures

Streamflow and sediment data for computing runoff and sediment yield of Reynolds Creek, subwatersheds, and upland source areas were obtained with the following equipment and procedures:

1. Special drop-box weirs were designed and constructed to measure streamflow heavily laden with sediment at source area and watershed runoff stations (Johnson, et al., 1966).
2. Suspended sediment pumping samplers were adapted for use at selected source area and watershed stations to automatically obtain samples during storms (Beverage and Skinner, 1968; Miller, et al., 1969).
3. USDH-48 depth-integrating suspended sediment hand samplers were used at source area and watershed stations, bridges, and other stream locations to monitor suspended sediment concentrations and calibrate pumping samplers.
4. Sediment detention ponds and tanks were constructed at source area stations to allow periodic measurement and sampling of coarse bedload material. Also, weir ponds were surveyed to determine sediment deposition during filling.
5. Helley-Smith bedload samplers (Helley and Smith, 1971) were adapted and used as follows: (1) 152-mm (6-in) orifice sampler was mounted on a backhoe for sampling from bridges; fine mesh (0.2-mm openings) and coarse mesh (1-mm openings) bags were

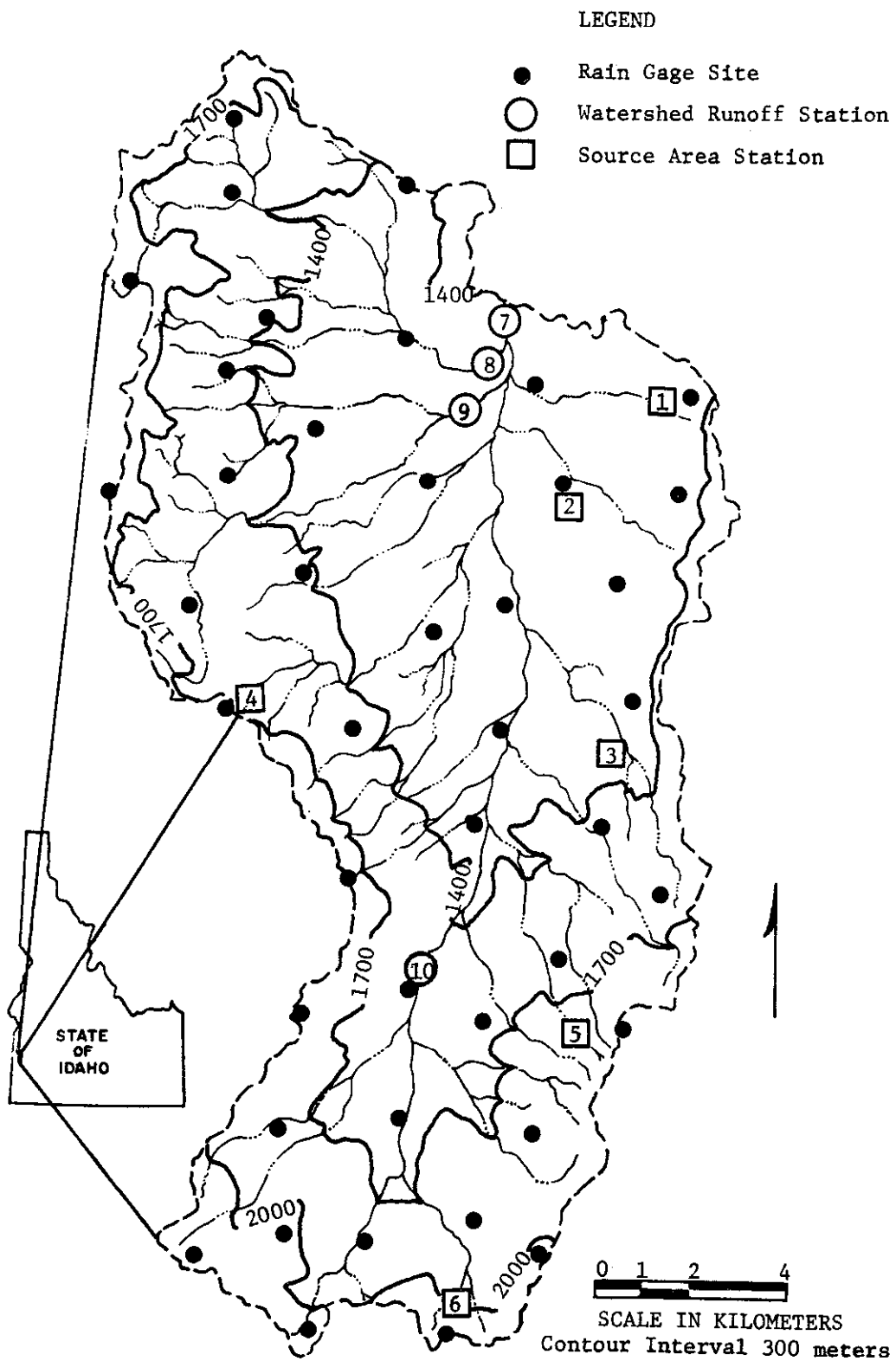


Figure 1. Reynolds Creek Experimental Watershed

used as conditions required; (2) 76-mm (3-in) orifice samplers with short handles were used in shallow streams where wading was possible (both fine and coarse bags were used); (3) 152-mm and 76-mm samplers with exchangeable long handles and bags were used with movable supports at bridge sampling stations; and (4) concrete sills were constructed across the channels at two locations to provide a smooth bottom for sampling in streams with boulder beds.

Runoff and sediment data from streamflow stations and sediment sample analyses were plotted and then processed with an analog to digital converter and computer to provide daily, monthly, and yearly summaries. Results were analyzed to determine relationships useful in evaluating and predicting sediment transport and yield from watersheds.

Results and Discussion

Upland source areas

Because of the extreme variability in precipitation and runoff at Reynolds Creek Watershed Stations, six upland source areas were instrumented for runoff and sediment measurement. Table 1 contains summary data for these source areas. Locations of the source area stations are shown in Figure 1.

Major runoff and erosion were caused by two thunderstorms at the Summit, by one occurrence of rain on snow and frozen soil at the Flats and Nancy Gulch, and by numerous snowmelt and rainfall events at Whiskey Hill, Upper Sheep, and Reynolds Mountain source areas. Characteristically, most of the sediment was transported by runoff from a few major storms (Johnson, et al., 1974b).

Watersheds

Downstream watersheds, instrumented for measuring streamflow and sediment, are described and data are summarized in Table 2; watershed runoff stations are shown in Figure 1. Salmon Creek, Macks Creek, and Reynolds at Tollgate are subwatersheds of Reynolds Creek at the Outlet. Scheduled sediment sampling began at Reynolds Outlet and Tollgate in 1967, and at Salmon and Macks in 1968. Sampling was discontinued whenever streamflow and sediment transport were visibly low. Yearly streamflow and sediment data from the four watersheds are listed in Table 3.

TABLE 1.--Source area data summary, water year basis, Reynolds Creek Watershed.

Information	Source Area					
	Summit	Flats	Nancy Gulch	Whiskey Hill ^{1/}	Upper Sheep	Reynolds Mountain
Location No.	1	2	3	4	5	6
Drainage area (ha)	83.02	.91	1.26	48.20	25.68	40.40
Ave. elevation (m)	1364	1188	1428	1684	1945	2082
Ave. precipitation (mm)	254	254	305	508	460	1040
Weir type	drop-box	V-notch	V-notch	V-notch	drop-box	drop-box
Type suspended sed. sampler	gravity	single stage	single stage	none	pumping	pumping
Years of record	7	3	3	10	5	8
Ave. runoff (mm/yr)	0.6	4.0	5.7	42.2	77.0	532.5
Peak streamflow date	6-19-69	1-18-72	1-18-72	--	3-2-72	6-6-72
mm/hr	6.23	1.85	1.71	--	0.30	1.58
m ³ /sec	1.42	.004	.006	--	.02	.18
ft ³ /sec	50.70	.16	.21	--	.77	6.25
Max. conc. (ppm)	--	1413	900	--	5000	1380
Ave. sed. yield (tonnes/ha/yr)	.76	.02	.04	.29	.31	.43
(tons/A/yr)	.34	.01	.02	.13	.14	.19

^{1/} Yearly sediment accumulations were measured in a lined pond. The sediment deposition efficiency of the pond was estimated at 90 percent.

TABLE 2.--Watershed descriptions and data summary for Reynolds Creek and sub-watersheds, water year basis.

Information	Watershed			
	Reynolds at Outlet	Salmon Creek	Macks Creek	Reynolds at Tollgate
Location No.	7	8	9	10
Drainage area (ha)	23369	3641	3177	5448
Ave. elevation (m)	1495	1485	1504	1861
Ave. slope (percent)	17.4	21.6	17.9	19.1
Ave. precipitation (mm)	500	480	485	777
Weir type	SCOV ^{1/}	drop-box	drop-box	drop-box
Runoff record (yrs)	12	10	9	9
Runoff record began	1963	1965	1966	1966
Sediment record (yrs)	8	7	7	8
Ave. runoff (mm/yr)	81.0	84.2	64.4	253.4
Ave. sediment yield (tonnes/ha/yr)	1.14	1.90	1.57	1.50
(tons/A/yr)	.51	.85	.70	.67

^{1/} SCOV is abbreviation for Self-Cleaning Overflow V-notch Weir (Bloomsburg and Tinney, 1961).

Bedload sampling and analysis

Bedload transport at Reynolds Outlet, Salmon Creek, Macks Creek, and Reynolds Tollgate Stations was determined by surveys of weir pond sediment accumulations and by use of Helley-Smith bedload samplers (Helley and Smith, 1971). Bedload, as a percentage of total sediment in transport, ranged from 7 to 50 percent and averaged 20 percent (*). Sediment yield data in Tables 2 and 3 include bedload amounts.

Organic debris (leaves, twigs, and roots) quickly plugged the openings in the fine mesh bags during channel flushing; therefore, data from fine mesh and coarse mesh samplers were combined to compute total bedload transport. The organic debris load during channel flushing events was often 10-20 percent of total bedload on a weight basis.

Sample results generally showed greater bedload amounts per unit orifice width from the 76-mm than from the 152-mm sampler, except when large gravel and boulders were moving. During a peak flow event with streamflow of $6.7 \text{ m}^3/\text{sec}$ ($240 \text{ ft}^3/\text{sec}$), 5-second sample weights exceeded 10 kg (22 lbs) and included rocks larger than 100 mm (4 in) in diameter.

Bedload transport at the Reynolds Outlet Station, during a series of storms, was 533 tonnes (588 tons) by bedload sampling and 635 tonnes (700 tons) by surveying downstream sediment deposits in an excavation. This comparison gives reasonable assurance that bedload sampling and computation procedures are acceptable, since some suspended material was also deposited in the excavation.

Suspended Sediment Prediction Model

A conceptual model was developed to predict suspended sediment discharge (m^3) at streamflow stations by runoff event. Events were easily identified on streamflow and sediment records and base flow data were included. Numerous small daily streamflow fluctuations were not considered events.

The model was:

$$SS = a (P \times V/100,000)^b \quad (1)$$

where:

(*) Written communication from William W. Emmett, Research Hydrologist, Water Resources Division, Geological Survey, U.S. Department of Interior, Denver, Colorado, reports that preliminary sediment-trapping calibration of the Helley-Smith samplers indicates near 100-percent efficiency.

SS = Total suspended sediment for the event (m^3)

P = Peak discharge (m^3/sec)

V = Total runoff (m^3)

a and b = model parameters.

TABLE 3.--Yearly peak flow rates, date of occurrence, runoff, maximum suspended concentration, and sediment yield, Reynolds Creek and subwatersheds, by water year.

Watershed	Year							
	1967	1968	1969	1970	1971	1972	1973	1974
<u>Reynolds Outlet</u>								
Peak flow(m^3/sec)	7.39	9.16	25.20	20.41	15.12	18.98	4.65	8.15
Date	6/7	2/21	1/21	1/27	1/18	3/2	4/17	3/29
Runoff(mm)	55.4	15.7	91.5	68.6	121.4	154.2	46.9	111.0
Max. conc.(ppm)	24700	16950	29170	15000	23000	14940	9990	6400
Sed. yield(tonnes)	19630	6300	57183	22343	41638	54365	3510	8377
<u>Salmon Creek</u>								
Peak flow(m^3/sec)	2.38	.95	5.85	5.88	3.70	5.63	1.54	1.48
Date	1/21	2/21	1/21	1/27	1/18	1/18	4/14	3/17
Runoff(mm)	67.6	22.3	91.5	88.6	103.4	142.6	54.5	84.1
Max. conc.(ppm)	--	20000	32850	16350	24000	38250	18400	5550
Sed. yield(tonnes)	--	551	12413	7349	7267	17905	2122	963
<u>Macks Creek</u>								
Peak flow(m^3/sec)	2.52	1.23	9.07	6.89	7.64	2.30	1.40	1.99
Date	1/21	2/21	1/20	1/27	1/18	6/9	4/14	3/14
Runoff(mm)	43.3	13.7	83.4	54.1	106.2	123.6	44.8	94.6
Max. conc.(ppm)	--	17850	20280	20300	19950	30000	16000	6930
Sed. yield(tonnes)	--	570	9205	5311	8480	7870	1838	1764
<u>Reynolds Tollgate</u>								
Peak flow(m^3/sec)	8.06	5.21	11.34	6.72	5.40	7.59	4.12	5.46
Date	6/7	2/21	1/21	1/27	5/6	3/2	4/17	3/29
Runoff(mm)	242.4	89.9	300.8	257.3	391.6	420.9	152.5	323.9
Max. conc.(ppm)	58810	8640	20000	5540	7010	8580	4710	5200
Sed. yield(tonnes)	13114	2286	15112	8422	11364	10280	1556	3242

An optimization technique was used to obtain the parameter values (Green, 1970).

Sediment yields from Tollgate, Salmon, Macks, and the Outlet Weirs were used in this analysis. Preliminary optimization runs indicated that model parameter b was near 1.0 in most cases; therefore, data were optimized in this manner. Parameter a was then determined (Table 4). As can be seen, the optimization fits the individual station data very well. Optimization of combined station events shows a lower correlation coefficient, but r values are still highly significant ($P < 0.01$), indicating that the model can be used for prediction.

TABLE 4.--Total event suspended sediment yield, parameter values, correlation coefficients (r), and number of events.

	Parameter		r	Number of events
	a	b		
Tollgate	44.5	1.0	0.89	92
Salmon	182.2	1.0	0.95	33
Macks	86.8	1.0	0.98	45
Outlet	35.8	1.0	0.98	62
Tollgate, Salmon, and Macks Combined	63.1	1.0	0.77	170
Tollgate, Salmon, Macks, and Outlet Combined	36.6	1.0	0.95	232

The mean suspended sediment yield for the events studied from the three combined watersheds was 500 m³ and ranged from 2.8 to 7,907 m³. The predicted mean was 515 m³. The average yield at the Outlet Weir was 2,057 m³ per event with a range of 21.1 to 32,730 m³. The average predicted yield was 2,162 m³ per event. Event data included about 90 percent of all suspended sediment during the period of record.

The value of parameter a at the Outlet is about one-half that from the other three watersheds, which indicates that considerably more suspended material is being transported from the three watersheds than from the whole Reynolds Creek Watershed under comparable runoff conditions. Deposition on irrigated fields and low yields from unmeasured tributaries probably account for the reduced transport at the Outlet.

Summary and Conclusions

Data from representative sagebrush rangeland watersheds in southwest Idaho show sediment yields average from 1.14 to 1.90 tonnes/ha/year (0.5 to 0.85 tons/ac/year). Yields in wet years are about tenfold higher than in dry years, with storms in January, February, and March yielding nearly 90 percent of the yearly sediment at the Reynolds Outlet station.

Sediment yields from 0.91- and 1.26-ha upland source areas were near zero during the 3-year period of record because no erosive storms occurred. Also, yields from four larger source areas, 25 to 83 ha, were only about one-third those of downstream watersheds. Steep, eroding streambanks and near-channel slopes obviously contribute greatly to larger downstream yields.

Bedload transport varied widely but averaged nearly 20 percent of total sediment load. Helley-Smith bedload samplers were adapted for sampling from bridges, but required both fine and coarse mesh bags to obtain complete information. Bedload samplers should be calibrated further to assure data accuracy.

The suspended sediment prediction model, using parameter optimization, shows excellent correlation between peak flow and runoff volume and suspended sediment amounts for identifiable runoff events. Application of this model to other streams with long-term runoff records should require sediment records from only a few events to determine values of parameter a . Studies relating model parameters to watershed characteristics are continuing.

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EROSION AND SEDIMENT YIELD IN NEW MEXICO ^{1/}

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ABSTRACT

Annual erosion in New Mexico is estimated to be between 50 and 119 million cubic meters (40,900 and 96,500 acre-feet). An estimated 74 percent of the erosion occurs on rangeland with lesser percentages on forest, urban, and crop land. Erosion in localized areas can be more than 15,242 cubic meters per square kilometer per year (32 acre-feet per square mile per year). Average annual sediment yield to reservoirs may be more than 4,334 cubic meters per square kilometer per year (9.1 acre-feet per square mile per year). Suspended sediment concentrations have been as high as 267,000 milligrams per liter in the Rio Puerco.

INTRODUCTION

High rates of erosion (by water) and sedimentation occur over large portions of New Mexico. Table 1 indicates an approximation of the annual erosion in the state as estimated during various levels of investigations conducted by Soil Conservation Service personnel in New Mexico.

The table indicates that the annual erosion is between 50 and 119 million cubic meters per year (40,900 and 96,500 acre-feet per year). For purposes of this paper, a figure of 81,500,000 cubic meters per year (66,120 acre-feet per year) is used.

<u>Erosion Rate</u> cu meters/sq km/yr (acre-feet/sq mi/yr)	<u>Area</u> sq km (sq mi) ^{2/}	<u>Total Erosion</u> million cu meters (1000 acre-feet)
>1429 (>3)	1036 (400)	>1.5 (>1.2)
476-1429 (1-3)	30,044 (11,600)	14.3-42.9 (11.6-34.8)
238-476 (0.5-1.0)	52,836 (20,400)	12.5-25.1 (10.2-20.4)
95-238 (0.2-0.5)	191,600 (74,000)	18.2-45.6 (14.8-37.0)
<95 (<0.2)	39,627 (15,300)	3.8 (<3.1)

Table 1. Annual Erosion in New Mexico (1)^{3/}

^{1/} For presentation at the Third Federal Interagency Sedimentation Conference, Denver, Colorado, March 22-26, 1976.

^{2/} Areas rounded off to the nearest one hundred.

^{3/} (1) See (1) of "Literature Cited."

The magnitude of erosion is shown relative to river basins within the state in Table 2.

<u>Basin</u>	<u>Drainage Area</u> sq km (sq mi)	<u>Percent of State</u> %	<u>Erosion</u> million cu meters (100 ac-ft)	<u>Percent of Total Erosion</u> %
Arkansas-White-Red	45,900 (17,722)	14.6	8.9 (7.26)	11
Upper Colorado				
San Juan	25,227 (9,740)	8.0	8.2 (6.64)	10
Rio Grande	195,188 (75,362)	66.2	55.0 (44.6)	67
Upper & Lower	127,710 (49,309)	40.6	37.0 (30.3)	46
Pecos	67,477 (26,053)	21.5	17.7 (14.3)	21
Texas-Gulf	14,211 (5,487)	4.2	2.4 (1.91)	3
Lower Colorado	34,589 (13,355)	11.0	7.0 (5.71)	9
Little Colorado	15,607 (6,026)	4.9	3.0 (2.83)	4
Gila	18,982 (7,329)	6.0	3.6 (2.88)	5

Table 2. Erosion Relative to River Basins in New Mexico (2)

When soil loss due to sheet, rill, and gully erosion is looked at broadly relative to land use, the following table can be constructed to indicate the relationship of erosion and land use.

<u>Land Use</u>	<u>Area</u> ^{1/} sq km million (sq mi)	<u>Erosion</u> ^{3/} metric tons/yr (million tons/yr)	<u>Percent of Loss</u>
Range	236,467 (91,300)	71.7 (79)	74
Forest ^{2/}	72,520 (28,000)	23.6 (26)	24
Urban, Crop, and Other Land	6,216 (2,400)	1.8 (2)	2

Table 3. Erosion in New Mexico Relative to Land Use (3)

^{1/} Area rounded off to nearest one hundred square miles.

^{2/} Includes pinyon-juniper lands.

^{3/} Unit weight assumed to be 1522 kg/cu m (95 pcf).

The above preliminary data indicate that each year about 97 million metric tons (107 million tons) of soil are transported in New Mexico due to sheet, rill, and gully erosion. Streambank erosion accounts for an additional 27.2 million metric tons (30 million tons) of eroded material in the state, bringing the total erosion from causes other than wind to more than 124 million metric tons (137 million tons) per year in New Mexico.

Using the 81,500,000 cubic meters (66,120 acre-feet) per year as the annual erosion for the state would indicate an average erosion rate of 257 cubic meters per square kilometer per year (0.54 acre-feet per square mile per year). When smaller areas (e.g., river basins within the state) are considered, it is noted that the erosion rates range between 167 and 327 cubic meters per square kilometer per year (0.35 and 0.68 acre-feet per square mile per year). When areas smaller than river basins are considered, it is noted in table 5 that the sedimentation in selected reservoirs may have a rate of accumulation of 4,334 cubic meters per square kilometer per year (9.1 acre-feet per square mile per year). When the delivery ratio for the watershed and trap efficiency of the reservoir are considered, the onsite erosion in the watershed could very well be more than 4,760 cubic meters per square kilometer per year (10 acre-feet per square mile per year).

Table 4 indicates the relationship between sheet and rill erosion and gully and channel erosion. In the selected watersheds, sheet and rill erosion may account for from 10 to 99 percent and gully and channel erosion from 1 to 90 percent of the total erosion. The relationship is also shown in table 6 for the Rio Puerco Watershed which is a major contributor of sediment to the Rio Grande above Elephant Butte Reservoir.

<u>Watershed</u>	<u>Sheet and Rill/Gully and Channel</u> %/%
Dona Ana Arroyo	10/90
Prop Canyon and Tributaries	36/64
Cass Draw	95/5
Upper Gila Valley Arroyos	19/81
Truth or Consequences-Williamsburg Arroyo	69/31
Running Water Draw	52/48
Eagle-Tumbleweed Draw	99/1
Tucumcari Draw	50/50

Table 4. Relationship of Sheet and Rill to Gully and Channel Erosion in Selected PL-566 Watersheds (4)^{1/}

^{1/} Estimates from PL-566 Watershed Work Plans.

Reservoir	Net Sed.	Period Yrs	Total Sediment Deposits	
	Contrib. Area		(ac-ft/yr)	(ac-ft/sq mi/yr)
	(sq mi) sq km		cu meters/yr	cu meters/sq km/yr

Arkansas-White-Red Region

Conchas	(6,976)	31.75	(2,273)	(0.326)
	18,068		2,802,040	155.3

Rio Grande Region
(Rio Grande Basin)

Abiquiu	(2,127)	4.58	(1,385)	(0.65)
	5,509		1,707,359	310
Jamez Canyon	(1,034)	5.8	(576)	(0.06)
	2,678		710,064	29
Santa Cruz	(93.1)	27.4	(25.7)	(0.27)
	241		31,682	129
Elephant Butte	(25,866)	54.3	(9,357)	(0.36)
	66,993		11,534,842	172
Caballo	(1,237)	19.9	(94.1)	(0.08)
	3,204		116,002	38
Santa Cruz River	(3.12)	6.7	(10.3)	(3.30)
W/S (#6)	8		12,697	1,572
Santa Cruz River	(1.16)	7.0	(10.5)	(9.1)
W/S (#3)	3		12,944	4,334
Zia	(2.4)	7.0	(5.84)	(2.43)
	6		7,199	1,157
Tortugas Arroyo	(20.54)	9.66	(14.3)	(0.69)
W/S (#1)	53		17,628	329

(Pecos Basin)

Upper Rio Hondo	(93.9)	12.9	(50.39)	(0.54)
W/S (#1)	243		62,118	257
Pecos Arroyo	(19.34)	6.7	(8.12)	(0.42)
W/S (#1)	50		10,010	200

Lower Colorado Region

Oak Creek	(9.41)	6	(31.2)	(3.32)
	24		38,461	1,581
Upper Gila Valley	(0.33)	8.7	(0.6)	(1.54)
W/S (#3)	0.9		740	733

Table 5. Sediment Accumulation in Selected Reservoirs in New Mexico (5)

	<u>Percent Sheet and Rill</u>	<u>Percent Channel and Gullies</u>
Upper Rio Puerco	48	52
Chico	63	37
Rio San Jose	76	24
Lower Rio Puerco	57	43

Table 6. Soil Production in the Rio Puerco Watershed (6)

SANTA CRUZ RIVER WATERSHED

The Santa Cruz River Watershed is an example of an area having a high erosion rate. This watershed is located on the western slope of the Sangre de Cristo mountain range in north central New Mexico and is in the Southern Rocky Mountains Physiographic Province. The average annual precipitation for the watershed, based on a nearby U.S. Weather Bureau station, is 25.4 centimeters (10 inches) per year. Major floods usually occur from high-intensity thunderstorms during the summer months. Within the watershed is located the reservoir of Site No. 3 (see table 5) which has a drainage area of 3.0 square kilometers (1.16 square miles). This drainage area can be divided into two sections: (1) the upper section consisting of extensively eroded Santa Fe Group strata (see photo No. 1) which is Tertiary in age and (2) a lower section of Quaternary alluvial deposits.



Photo No. 1. Santa Fe Group Strata, New Mexico.

The Santa Fe Group of strata consists primarily of weakly cemented sandstone and siltstone, and geologic erosion is considered rapid. The alluvial deposits consist of sands and silty sands with minor occurrence of gravels.

The highly eroded part of the Santa Fe Group is referred to as "badlands" and the valley fill is considered "rangeland" for purposes of this paper. The average slope of the "badlands" area is 70 percent and the average slope of the "rangeland" is 16 percent. Vegetative cover is essentially zero in the "badlands" and ranges from 5 to 10 percent on the "rangeland."

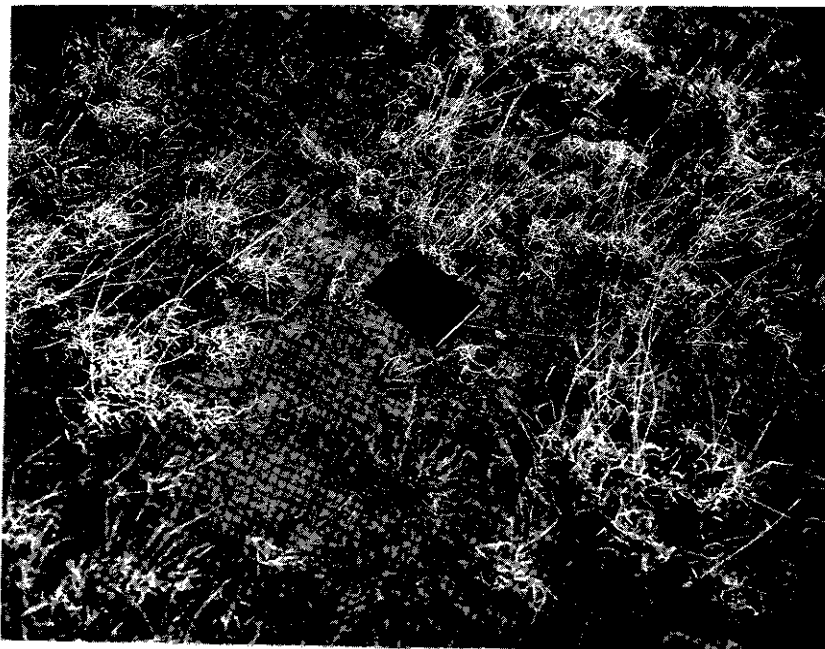


Photo No. 2. Vegetative Cover on Rangeland in Santa Cruz Watershed, New Mexico.

The contributing drainage area of 3 square kilometers (1.16 square miles) contains approximately 67 percent "badlands" and 33 percent "rangeland."

Sedimentation surveys conducted on the reservoir indicated an average annual accumulation of 12,944 cubic meters (10.5 acre-feet) in a period of 7.0 years for an average annual rate of 4,334 cubic meters per square kilometer (9.1 acre-feet per square mile). In this reservoir between January and October of 1969 approximately 46,230 cubic meters (37.5 acre-feet) of sediment was deposited.

RIO PUERCO WATERSHED

A second watershed which contributes large quantities of sediment to the Rio Grande is the Rio Puerco. This watershed, with a drainage area of 19,011 square kilometers (7,340 square miles), is the largest tributary to the Rio Grande in New Mexico. The watershed is approximately 201 kilometers (125 miles) in length and about 137 kilometers (85 miles) wide. It lies principally within the Colorado Plateau Physiographic Province with the northeast portion of the watershed in the Sierra Nacimiento and San Pedro Mountains of the Southern Rocky Mountains Physiographic Province.

In the mountains or headwaters, the stream flows through reasonably stable gravel channels which, as they leave the mountains, develop into sheer-walled tortuous arroyos that vary from 6.1 to 15.2 meters (20 to 50 feet) in depth and from 12.2 to nearly 305 meters (40 to 1,000 feet) in width. The average annual precipitation varies from less than 17.78 centimeters (7 inches) in the lower elevation to about 43.18 centimeters (17 inches) in the mountains. About 50 percent of the annual precipitation occurs during the 3-month period of July through September, usually in the form of brief but often intense thundershowers.

Rocks range in age from Precambrian to Recent and include sedimentary, metamorphic, and igneous intrusive and igneous extrusive.

The alluvial soils are of special interest relative to erosion problems. They are characterized by deep soil profiles and occupy the flood plains and terraces. The soils crack easily and result in the piping conditions that occur in most of the alluvial soils (see photo No. 3).

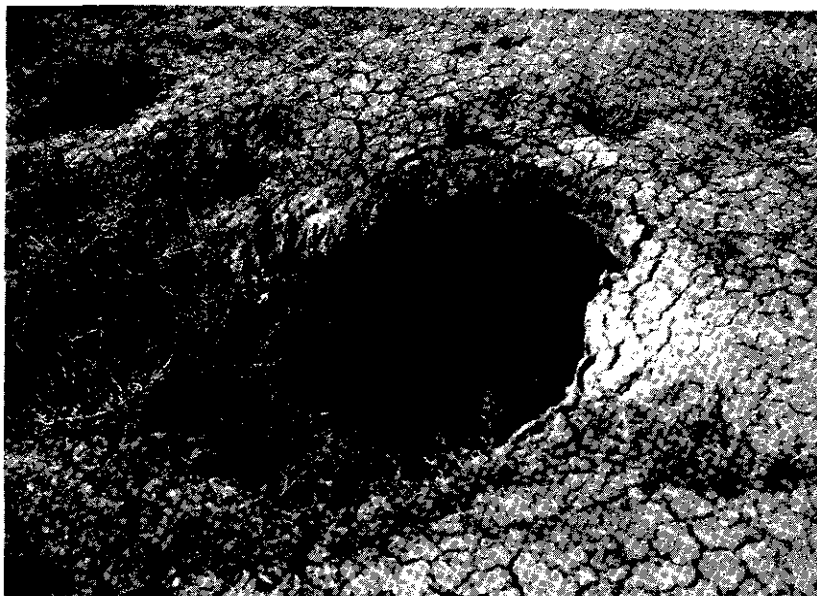


Photo No. 3 Piping in the Rio Puerco Watershed, New Mexico.

This piping condition may extend long distances underground before entering the lower entrenched drainages. This furnishes an opportunity for penetration and concentration of water and, as a result, along the sides of the vertical banks of the stream channels (see photo No. 4) and gullies, there is considerable caving in and sloughing off of earth blocks.



Photo No. 4. Sloughing off of Banks in the Main Channel of the Rio Puerco, New Mexico.

The magnitude of erosion in the watershed and sediment yield to the Rio Grande is indicated from data collected at a sediment measuring station located 4.83 kilometers (3 miles) upstream from the mouth. Between October 1963 and September 1964, more than 2,917,000 tons of suspended sediment passed this station. This may appear to be considerable material, but on August 7, 1957, approximately 2½ million tons passed the station. The maximum suspended sediment concentration to pass the station is 267,000 mg/l which occurred July 26, 1957. (7)

CONCLUSION

Preliminary data indicate that each year about 97 million metric tons (107 million tons) of soil are lost in New Mexico due to sheet, rill, and gully erosion. A study recently completed by the Soil Conservation Service indicates that if land treatment were installed on approximately 18 thousand square miles, the soil loss due to sheet, rill, and gully erosion could be reduced by approximately 16 million tons per year. This represents a 15 percent reduction. (3)

This reduction in erosion and the consequent reduction in sediment yield to urban and crop land, rivers, and reservoirs would have substantial impact on improving the environment as well as on reducing economic damages.

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DEBRIS FLOWS FOLLOWING WILDFIRE IN NORTH CENTRAL WASHINGTON

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ABSTRACT

A combination of rapid snowmelt, high intensity rainstorms, and fire-denuded watersheds resulted in massive debris torrents from numerous tributary streams of the Entiat River in north-central Washington during the spring and summer of 1972. Debris torrents are summarized by location, soil type, topography, and land use history for five adjacent watersheds. Alternative forest management recommendations are suggested for minimizing the impact of possible future debris torrents within the study area.

INTRODUCTION

An alluvial fan at the mouth of almost every tributary stream of the Entiat River in north-central Washington testifies to the occurrence of debris torrents during past centuries. Many new debris torrents during the spring and summer of 1972 provided an unusual opportunity for insight into the geologic, topographic, soil, vegetative, and climatic conditions which are associated with debris torrents in this area. The purpose of this paper is to document the conditions which led up to several debris torrents in the Entiat Experimental Forest and two adjacent watersheds, to point out forest conditions which possibly helped initiate debris torrents, and to suggest some precautions for forest managers who operate on these steep, unstable areas.

STUDY AREA

The study area is located in the Entiat River Valley which meets the Columbia River about 32 kilometers (20 miles) north of Wenatchee, Washington. The upper reaches of this southeasterly draining valley show typical evidence of glaciation during the late Wisconsin stage of the Pleistocene epoch. However, the upper slopes of the valley show little evidence of mountain glaciation. Thus, many tributary streams appear as hanging valleys above the present valley floor. During glaciation, the lower reaches of these hanging valleys were filled with flowing glacial sediments. Since glaciation, streamflow has deeply incised these highly unstable sediments. At the base of the hanging valley on most tributaries, alluvial fans consisting of large boulders and sediments have developed, apparently the result of debris flows.

Our particular study area within the Entiat Valley for discussion is the three watersheds on the Entiat Experimental Forest--Fox, Burns, McCree--and two adjacent watersheds--Brennegan and Preston (Figure 1). These five watersheds contain about 5000 hectares (12,350 acres) in total area and are located at latitude 47° 57' N and longitude 120° 28' W. Watershed elevations range from about 550 to 2100 meters (1,800 to 7,000 feet) above sea level. The mean slope level is about 50 percent, but slopes of 90 percent are common. All five watersheds were severely burned by wildfire in August 1970.

Bedrock consists primarily of granodiorite and quartz diorite. All five watersheds are characterized by hanging valleys with deeply incised fluvioglacial material above the cutoff wall. Since the glacial period, much of the watersheds has been covered by deposits of pumice and ash originating principally from Glacier Peak, 56 kilometers (35 miles) to the northwest. Depth of this volcanic material ranges from a few centimeters to more than 6 meters (20 feet).

Before the fire, vegetation on slopes between 550 and 915 meters (1,800 to 3,000 feet) elevation consisted of an overstory of ponderosa pine (Pinus ponderosa Laws.), with an understory of bitterbrush (Purshia tridentata (Pursh) DC.) and serviceberry (Amelanchier alnifolia Nutt.). At elevations between 915 and 1675 meters (3,000 to 5,500 feet), Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) became more prominent in the overstory, with occasional small dense thickets of lodgepole pine (Pinus contorta Dougl.). These thickets appear to be in areas burned by wildfire in the recent past. Understory was predominantly snowbrush (Ceanothus velutinus Dougl.), willow (Salix spp.) Sitka alder (Alnus sinuata (Reg.) Rydb.), and kinnikinnick (Arctostaphylos uva-ursi (L.) Buckl.). At elevations above 1750 meters (5,740 feet), whitebark pine (Pinus albicaulis Engelm.) was common.

Much of the lower elevations within Preston and Brennegan watersheds was selectively logged before 1970. Fire salvage logging along with associated road construction proceeded in all watersheds in 1971 and 1972 except at Fox, which was retained as an unlogged and unroaded control watershed. Fire salvage logging was predominantly by jammer and tractor in Brennegan and Preston, with most salvage yarded by helicopter or tractor over snow in Burns and McCree. The impact of this logging on soils and vegetation is discussed by Klock (1975).

SEDIMENTATION ACTIVITY

Prefire

Sediment monitoring was begun about 1958 on Fox, McCree, and Burns watersheds. The watersheds appeared to be stable under natural conditions, and sediment trapped by weirs was extremely low. Weir ponds on Burns and McCree did not require cleaning from the time of installation until the 1970 fire. Fox Creek flows through an area where side slopes are oversteepened and sparsely vegetated between 850 and 915 meters (2,800 to 3,000 feet). Soil material dry raveled into

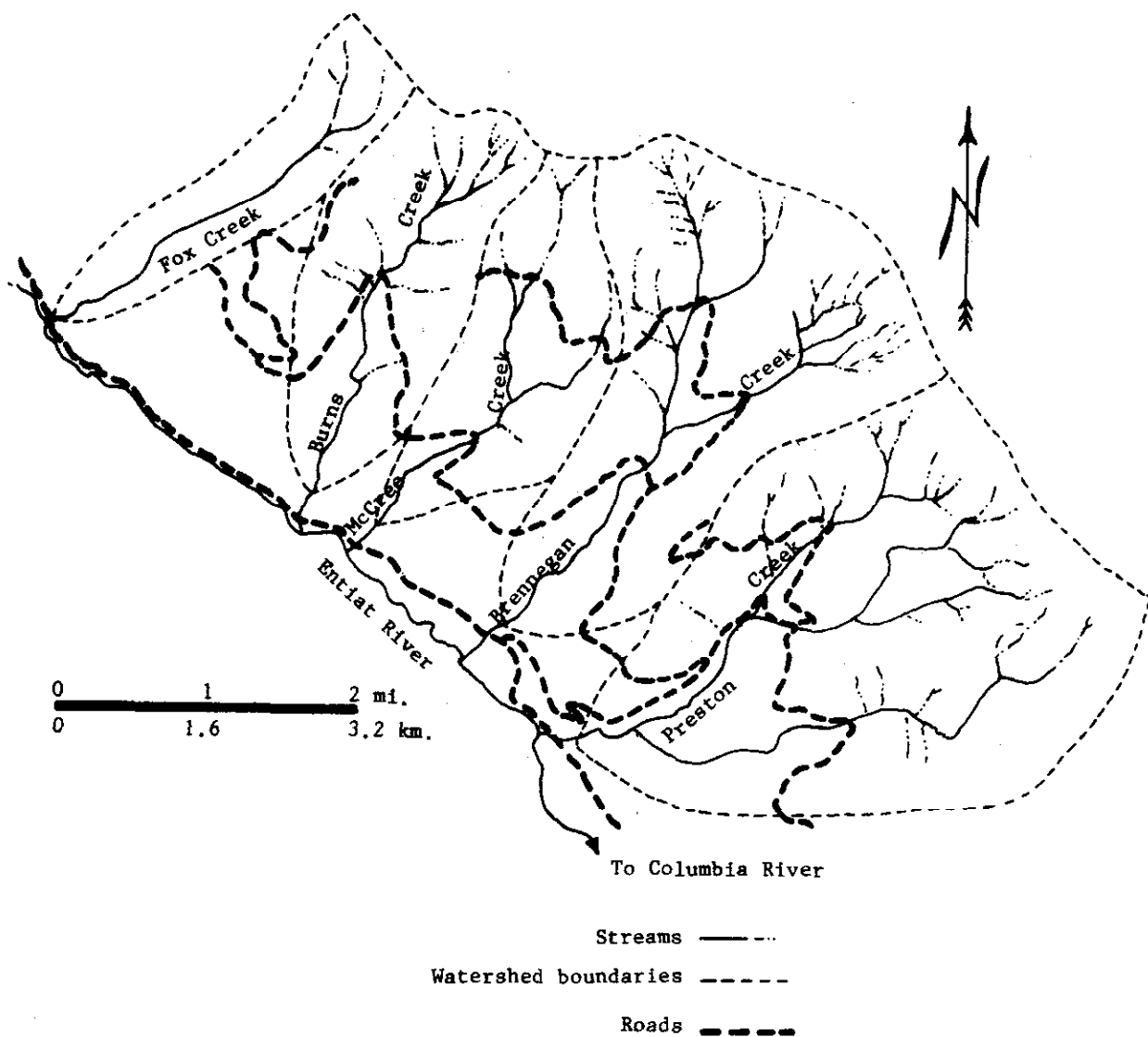


Figure 1. The study area is located in north-central Washington.

the stream channel during the summer months, and spring runoff carried it to the weir pond where it was trapped for measurement. Annual bedload on the 473-hectare (1,168-acre) Fox watershed ranged from 4.5 to 16.3 metric tons (5 to 18 tons) and averaged 10.9 metric tons (12 tons) between 1966 and 1970. Unfortunately, there are no prefire data for suspended sediment production. Typical values as determined from later studies might be 12 kilograms per hectare per year, or an average annual load of 5.7, 6.8, and 6.2 metric tons for Fox, Burns, and McCree watersheds, respectively.

Postfire

Maximum daily streamflow rates in 1971, the first runoff season following the fire, were nearly double the maximum flow measured during the 11-year watershed calibration period (Helvey, 1973). Thus, the increased streamflow was responsible for channel enlargement and consequent increases in sediment deposition in the catchment basins. Sediment in 1971 measured 162, 126, and 52 metric tons (179, 139, and 57 tons) for Fox, Burns, and McCree watersheds, respectively. An additional 9.9 metric tons (10.9 tons) of sediment were collected behind the McCree Creek weir in the fall of 1971. Virtually all of this material appeared to come from upstream road construction. All sediment values reported here must be considered an estimate, because most of the sediment was collected in a very short time while streamflow was quite high. Undoubtedly some sediment flushed through the traps and was not measured. In any case, bedload sedimentation levels the first year following wildfire were considerably greater than those monitored before destruction of the vegetation by fire.

In the fall of 1971 soil moisture measurements showed increased soil moisture storage in the fire-affected area because of greatly reduced transpiration losses (Klock and Helvey, 1975). In fact, the volume of additional water stored in the soil profile was almost equivalent to average annual runoff measured before the fire. On the basis of these soil moisture measurements, we predicted that the watersheds were very sensitive hydrologically and that considerable mass soil movement was likely during the following spring runoff season.

During mid-March 1972, unseasonable warm weather hastened snowmelt from a record high snowpack in the Entiat Valley, and considerable mass soil movement occurred below 1050-meter (3,500-foot) elevation, particularly in areas burned by the 1970 wildfire. In our study area two debris torrents occurred, one on Preston and another on McCree. Both torrents appeared to be initiated by excessive pore water pressure in small pockets on very steep granitic slopes. In both locations the soil pocket was in the dip slope of the rock structure. The Preston debris torrent on the lower west side of the watershed did not affect the stream channel, but it did deposit approximately 1000 cubic meters (1,300 cubic yards) of rock, mud, and wood debris on or near the highway. The initial

torrent in McCree crossed a newly constructed road, picked up some construction debris on the downslope, and proceeded to the stream channel. The debris blocked the McCree Creek channel momentarily. Water appeared to reach depths of perhaps 6 to 7 meters (20 feet) before the temporary dam broke, releasing a torrent into the Entiat River about 800 meters (0.5 mile) downstream. The stream channel was scoured to a depth of about 5 meters (15 feet); the stream gaging and sediment collection station was destroyed; and several thousand cubic meters of debris were deposited on the alluvial fan. An unknown but substantial amount of debris was carried to the Entiat River.

About midday on June 9, 1972, a high intensity rainstorm (records show about 335 millimeters of rainfall in 2 hours) struck the upper reaches of the Fox watershed. Shortly thereafter, a debris torrent occurred on Fox Creek, depositing several thousand cubic meters of debris, including many large logs, on the alluvial fan and in the Entiat River. Significant damages occurred, including loss of the stream and sediment gaging station and the loss of about 20 meters (65 feet) of the highway. The flow appeared to be exceedingly violent. A raingage located approximately 16 meters (50 feet) above the channel near the gaging station was destroyed by the torrent.

In the early morning hours of June 10 another high intensity rainstorm struck the watersheds. A recording raingage at the 1341-meter (4,400-foot) elevation between McCree and Brennegan showed 584 millimeters (2.3 inches) of rainfall during this period, with maximum intensity of about 282 millimeters/hour (1.1 inches/hour). As was the case of the storm on the previous day in the Fox watershed, the heavy rainfall occurred on the rocky uplands, where little soil water retention capacity is available. Coupled with the already fully charged soil profile in the lower watershed soils, overland flow occurred and record volumes of streamflow developed. With the record flow and a high stream channel resistance from debris, constrictions, etc., a wave appeared to develop, creating a debris torrent on Preston, Brennegan, and again on McCree and Fox. The torrent on McCree and Fox basically added additional volumes of sediment to the already disturbed alluvial fans at the mouth of these watersheds. On Preston Creek all forks were scoured from the upper reaches of the stream channel, with maximum channel scouring occurring in the deeply incised canyon starting about 1500 meters (5,000 feet) above the glacier-formed cutoff wall. A massive volume of debris, including very large boulders, flowed out on the alluvial fan in an obviously fast and violent manner. Several private cabins on the fan were completely destroyed and four people killed. On Brennegan, high flow and channel scouring were also evident from the highest water source area in the watershed. A very large volume of debris was also deposited on the alluvial fan and in the Entiat River.

As if "enough was not enough," heavy rainstorms again returned in mid-August of 1972, causing additional debris torrents with sediment deposition from Fox and McCree. Although heavy sedimentation from slides and road washouts made sediment monitoring impossible on Burns watershed, this was the only drainage in the study area in which a debris torrent did not develop. No explanation is readily available on why this watershed was spared when watersheds on both sides produced debris torrents.

Basically two types of conditions developed which initiated debris torrents within the study area. The first was the midslope "blow out," where a small pocket of soil was violently displaced by high pore water pressures. These high pore water pressures were generated by cold snowmelt water in areas of restricted drainage. Loose debris below the initial soil displacement added to the intensity of the torrent. The second type of torrent observed was developed by high intensity rainstorms on steep mountain slopes characterized by rock surface with little infiltration capacity or by hydrologically sensitive soils near saturation. Streamflow volume increased very rapidly from the overland flow inputs. Sudden high stream flow volumes connected with high channel resistance appear to have allowed a very large wave to develop. This wave carried massive amounts of debris which was responsible for the serious destruction that was highly visible in the June 10 torrent in Preston Creek.

Both types of torrent appear to have occurred periodically for centuries. We could speculate from tree age and soil morphologic evidence on the alluvial fans that torrent frequency is as often as every 80 to 150 years. Although we are yet unable to correlate wildfire frequency with frequency of debris torrents, there probably is a relationship. We reason that any land condition which increases the hydrologic sensitivity of the watershed, such as wildfire or vegetation removal by clearcut logging, will increase the probability of debris torrents within the affected area.

Creep is very evident in the soil material adjacent to the streams within the study area. We have estimated movement rates from tree displacement as great as 2.5 centimeters (1 inch) per 10 years. Creep continues to fill the channels with soil debris until they are scoured by a torrent. Streambanks are oversteepened by the scouring action; and creep, along with other mass soil movement processes, is accelerated to complete the cycle by refilling the channel.

MANAGEMENT IMPLICATIONS

Our investigation within the study area pointed out several areas where forest management can reduce, but not eliminate, the hazards of debris torrents within the region. Obviously, the prevention or control of wildfire may reduce the probability of debris torrents. Forest harvest practices which increase soil moisture levels and significantly increase the hydrologic sensitivity of a watershed should be carefully studied and evaluated in terms of soils and topographic features for each cutting unit. More research is also needed in defining the level of soil moisture which makes a watershed significantly hydrologically sensitive. Management activities within the riparian zone should attempt to reduce the accumulation of debris within the stream channel. Logging slash and road construction debris could possibly increase or even initiate wave action in the stream channel. Megahan (1972) showed that road construction can increase streamflow volumes by interception and conversion of groundwater to streamflow. Increased streamflow volumes can also increase the probability of debris torrents. Thus, road design should be evaluated with respect to its possible effect on streamflow in critical areas, particularly in areas similar to our study watersheds. However, even with the best physical land management there still exists the probability of debris torrents in the area we have evaluated. Only by proper land use planning or the control of man's activity on these alluvial fans can we minimize the possibility of the tragic loss of life and property.

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SEDIMENT YIELDS FROM A MISSISSIPPI DELTA WATERSHED

By C. E. Murphree, Agricultural Engineer, C. K. Mutchler, Hydraulic Engineer, and L. L. McDowell, Soil Scientist, USDA Sedimentation Laboratory, Oxford, Mississippi.

ABSTRACT

Runoff and sediment yield were measured on a Mississippi Delta watershed, land-formed to 0.2 percent slope, and farmed in continuous cotton. Interest in sediment yields and hydrology of the flatland watersheds of the Lower Mississippi River Valley or Delta (as it is commonly known) has increased greatly due, primarily, to the concern that agricultural chemicals may be transported into streams and lakes by sediment and runoff waters from farmlands. However, sediment yields indicate a serious erosion problem; 28.98 MT/ha/year (12.93 tons/acre/ year) were lost from a 15.58-ha (38.5-acre) watershed during a 2-year period. Because rainfall in these 2 years was extremely high (33 percent above the 17-year average), long-term average annual sediment yield values should be lower.

INTRODUCTION

The agricultural lands of the Lower Mississippi River Valley or Delta (as it is commonly known) are intensively tilled. Because of the high clay content of many soils in the area and high soil moisture levels during winter and early spring, seedbed preparation for the next crop begins at the first opportunity after harvest in the fall or early winter. This practice leaves the soil disturbed and without cover through most of the wet season; consequently, erosion rates are high and sediments, consisting primarily of clays and silts, deposit in ditches, drainage canals and lakes of the area. Periodic maintenance is then required to maintain channel capacities to meet drainage requirements. Little research has been done, previously, to determine the magnitude of erosion and sediment problems on these relatively flat slopes.

The Mississippi Delta is noted for cotton production, which requires extensive use of farm chemicals. Since many of these chemicals move while attached to eroding soil particles, knowledge of erosion and sediment transport phenomena is necessary to compute chemical yields in runoff. In this study, we determined runoff and sediment yields from a Delta watershed, managed by conventionally accepted practices of the area, to provide basic data for an analytical study of farm chemical concentrations and yields in runoff. This paper discusses the magnitude of the sediment yield problem on Delta watersheds with Sharkey soil and provides preliminary information on runoff and sediment transport from these nearly flat lands.

WATERSHED AREA AND INSTRUMENTATION

The study watershed is on the G. L. McWilliams Farm near Clarksdale, Mississippi. The drainage area is 15.58 ha (38.5 acres) and is the north watershed indicated on Figure 1. The land was formed to a slope of 0.2 percent with 1.02-m (40-inch) rows up and down slope in a north-south direction. Runoff generally follows each individual row until it enters the main east-west V-ditch and then flows into the pond through a Parshall flume, Gaging Station 802 on Figure 1. The mean slope length of the rows in the watershed is 186 m (610 feet).

The soil on the entire watershed is Sharkey silty clay. The erodible soils at the 0- to 15-cm (0- to 0.5-foot) depth contain 47 percent clay ($<2\mu\text{m}$) and only 0.6 percent sand ($>0.063\text{ mm}$). The geometric mean diameter of the surface soils is $2.5\mu\text{m}$.

Precipitation data were obtained with a recording raingage near gaging station 802, Figure 1. A standard 0.91-m (3-foot) Parshall flume was used to measure the runoff with two digital punch tape recorders, synchronized for simultaneous stage-time recording at 5-minute intervals. Waterstage records were required at both converging and diverging sections of the flume because some submergence occurs. Instantaneous point samples of runoff were collected at the gaging site with a US-PS-69 automatic pumping sampler (St. Anthony Falls Hydraulics Laboratory, 1974; Murphree, et al., 1972). A sample was taken at 10-minute intervals when the water was 6.1-cm (0.20-feet) or more deep, and at the same time as the water stage and time were recorded by the digital waterstage recorder.

PRECIPITATION

Average annual precipitation for 1941-1970 at Clarksdale, MS (approximately 17.7 km (11 miles) to the southeast) was 125.35 cm (49.35 inches) (U. S. Department of Commerce, 1974). Precipitation at the watershed was 165.89 cm (65.31 inches) for the water year beginning July 1972 and 174.40 cm (68.66 inches) for the water year beginning July 1973 (Tables 1 and 2). Rainfall was extremely high during both years, 32 and 39 percent above the 30-year average.

CROP MANAGEMENT

The entire watershed has been planted to cotton for many years. Records are maintained throughout the year on tillage practices, ground cover, crop cover, and other management practices that may affect erosion and sediment yields. Tillage practices followed closely those recommended for the area. Several different tillage methods are used for seedbed preparation, depending on weather, soil moisture, grass and weed problems, and time available at planting. However, the following tillage sequence is typical:

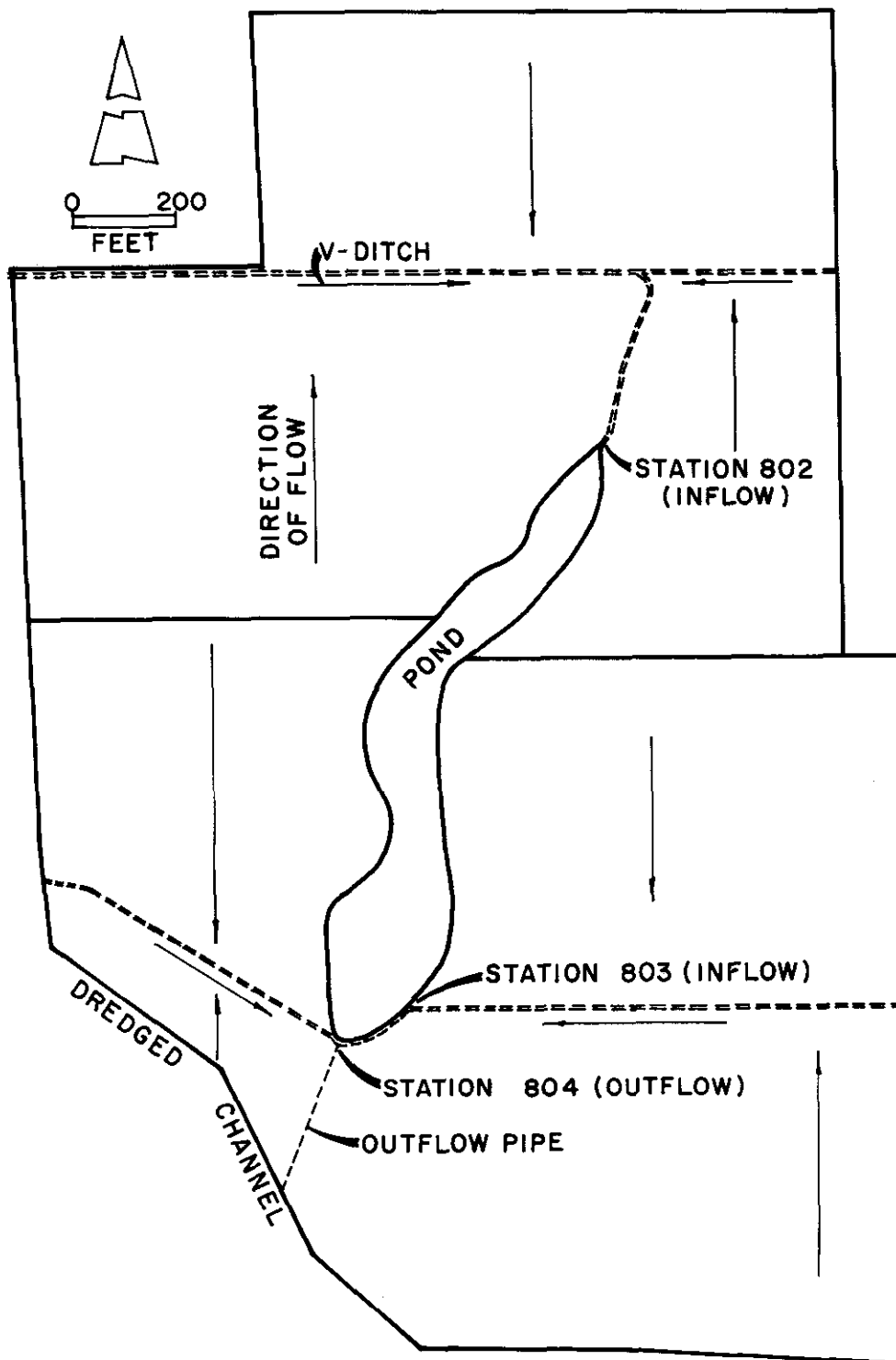


Figure 1--McWilliams Watershed Map.

Fall after harvest:

Cut or shred stalks
Chisel plow at angle to rows
Disk lightly with a tandem disk

Spring and Summer

Disk with tandem disk
Bed with disk hipper
Pulverize soil with Do-All^{3/} or similar equipment; apply preplant herbicide
Bed with disk hipper and apply nitrogen fertilizer
Pulverize soil with Do-All^{3/} or similar equipment
Plant cotton and apply preemergence herbicide
Cultivate cotton several times and apply postemergence and layby herbicides for weed control.

RESULTS AND DISCUSSION

Storm events were analyzed separately to determine runoff and sediment yield. Monthly and yearly amounts of rainfall, departures from normal rainfall, runoff, sediment yield and discharge-weighted concentrations are given in Tables 1 and 2 for the first and second water years of the study. When a storm began on the last day of a month, the rainfall, runoff, and sediment yield were included in the record for that month.

In both years, the weather permitted tillage to begin during February. As a result, the soil was in a tilled or disturbed condition from February through July, with little or no cover until mid-July when crop canopy approached 80% cover. During August-January the soil was undisturbed by tillage and was covered by a crop canopy (August-October) and crop stubble (November-January). Data for these periods of different watershed erodibility show that sediment yields per unit of rainfall were much higher during February-July than during August-January (Figure 2). Runoff as a proportion of rainfall was also less in August-January.

The effects of tillage on sediment yield are also evident when studying individual storm runoff volumes and sediment yields. Individual storm values, grouped by tilled period (February-July) and untilled, good cover period (August-January) are shown on Figure 3.

A regression analysis of the storm sediment yield-runoff values as a power function relationship resulted in an exponent of nearly one for both periods. This allowed a representation of the data on a rectilinear basis, (Figure 3). The resulting relationships were

^{3/} Trade names are provided for information only and do not imply endorsement by the U. S. Department of Agriculture.

Table 1.--Monthly Amounts of Rainfall, Runoff, Sediment Yield and Concentrations, McWilliams Watershed 802, July 1972-June 1973.

<u>Month/Year</u>	<u>Rainfall</u>		<u>Departures^{1/}</u>		<u>Runoff</u>		<u>Sediment Yield</u>		<u>Concentration^{2/}</u>
	<u>cm</u>	<u>inches</u>	<u>cm</u>	<u>inches</u>	<u>cm</u>	<u>inches</u>	<u>MT/ha</u>	<u>tons/acre</u>	<u>mg/l</u>
July 1972	9.93	3.91	0.33	0.13	0.36	0.14	0.07	0.03	1891
August 1972	3.28	1.29	- 3.10	- 1.22	0	0	0	0	--
September 1972	5.69	2.24	- 2.29	- 0.90	0	0	0	0	--
October 1972	10.31	4.06	3.99	1.57	0.99	0.39	0.07	0.03	679
November 1972	21.31	8.39	10.49	4.13	12.17	4.79	1.50	0.67	1234
December 1972	21.92	8.63	9.42	3.71	14.35	5.65	2.60	1.16	1812
January 1973	13.61	5.36	1.40	0.55	7.72	3.04	1.77	0.79	2293
February 1973	2.75	5.02	0	0	9.93	3.91	2.87	1.28	2889
March 1973	23.85	9.39	10.06	3.96	12.42	4.89	7.26	3.24	5848
April 1973	21.51	8.47	8.20	3.23	14.83	5.84	7.02	3.13	4730
May 1973	12.65	4.98	0.69	0.27	4.70	1.85	2.98	1.33	6345
June 1973	<u>9.07</u>	<u>3.57</u>	<u>1.35</u>	<u>0.53</u>	<u>3.35</u>	<u>1.32</u>	<u>2.67</u>	<u>1.19</u>	<u>7957</u>
Annual total	165.89	65.31	+40.54	+15.96	80.82	31.82	28.81	12.85	3564

^{1/} Departures from monthly normal, period 1941-1970

^{2/} Discharge weighted mean concentration

Table 2.--Monthly Amounts of Rainfall, Runoff, Sediment Yield and Concentrations, McWilliams Watershed 802, July 1973-June 1974.

<u>Month/Year</u>	<u>Rainfall</u>		<u>Departures^{1/}</u>		<u>Runoff</u>		<u>Sediment Yield</u>		<u>Concentration^{2/}</u>
	<u>cm</u>	<u>inches</u>	<u>cm</u>	<u>inches</u>	<u>cm</u>	<u>inches</u>	<u>MT/ha</u>	<u>tons/acre</u>	<u>mg/l</u>
July 1973	12.32	4.85	2.72	1.07	1.83	0.72	0.31	0.14	1716
August 1973	4.67	1.84	- 1.70	- 0.67	T	0 ^{4/}	T	0 ^{3/}	--
September 1973	6.20	2.44	- 1.78	- 0.70	0.13	0.05	0.02	0.01	1765
October 1973	7.57	2.98	1.24	0.49	0.03	0.01	T	0 ^{3/}	--
November 1973	21.69	8.54	10.87	4.28	12.57	4.95	2.35	1.05	1872
December 1973	11.86	4.67	- 0.64	- 0.25	5.69	2.24	1.46	0.65	2561
January 1974	22.61	8.90	10.39	4.09	15.27	6.01	2.76	1.23	1806
February 1974	8.81	3.47	- 3.94	- 1.55	3.40	1.34	2.11	0.94	6191
March 1974	4.88	1.92	- 8.92	- 3.51	0.23	0.09	0.04	0.02	1961
April 1974	12.95	5.10	- 0.36	- 0.14	6.07	2.39	2.29	1.02	3767
May 1974	37.85	14.90	25.88	10.19	26.64	10.49	10.09	4.50	3786
June 1974	<u>22.99</u>	<u>9.05</u>	<u>15.27</u>	<u>6.01</u>	<u>15.88</u>	<u>6.25</u>	<u>7.71</u>	<u>3.44</u>	<u>4858</u>
Annual total	174.40	68.66	+49.05	+19.31	87.73	34.54	29.14	13.00	3322

^{1/} Departures from monthly normal, period 1941-1970

^{2/} Discharge weighted mean concentration

^{3/} Less than 0.011 MT/ha (.005 tons/acre)

^{4/} Less than 0.013 cm (.005 inches)

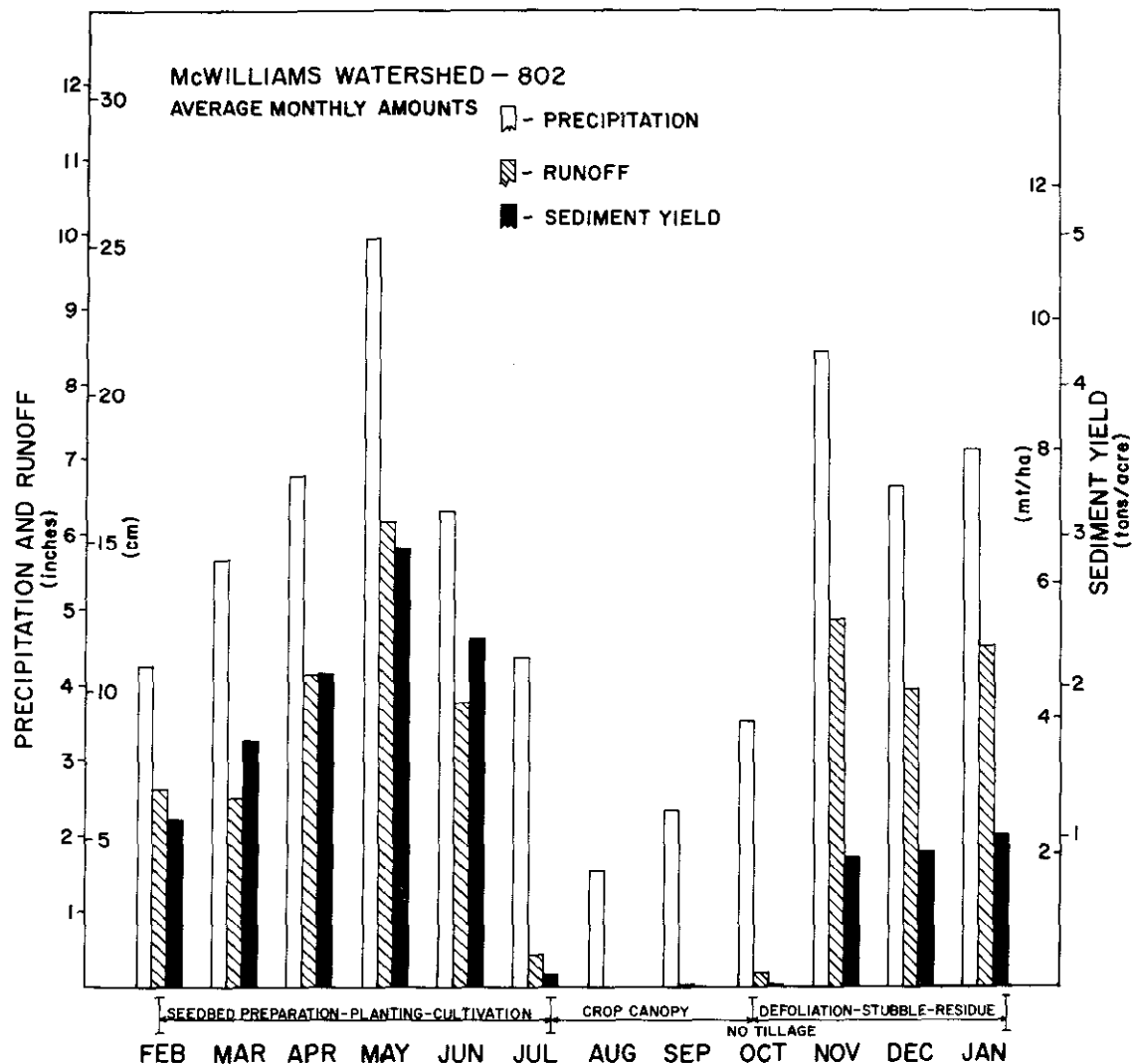


Figure 2--Average Monthly Amounts of Rainfall, Runoff, and Sediment Yield: July 1972-June 1974, McWilliams Watershed 802.

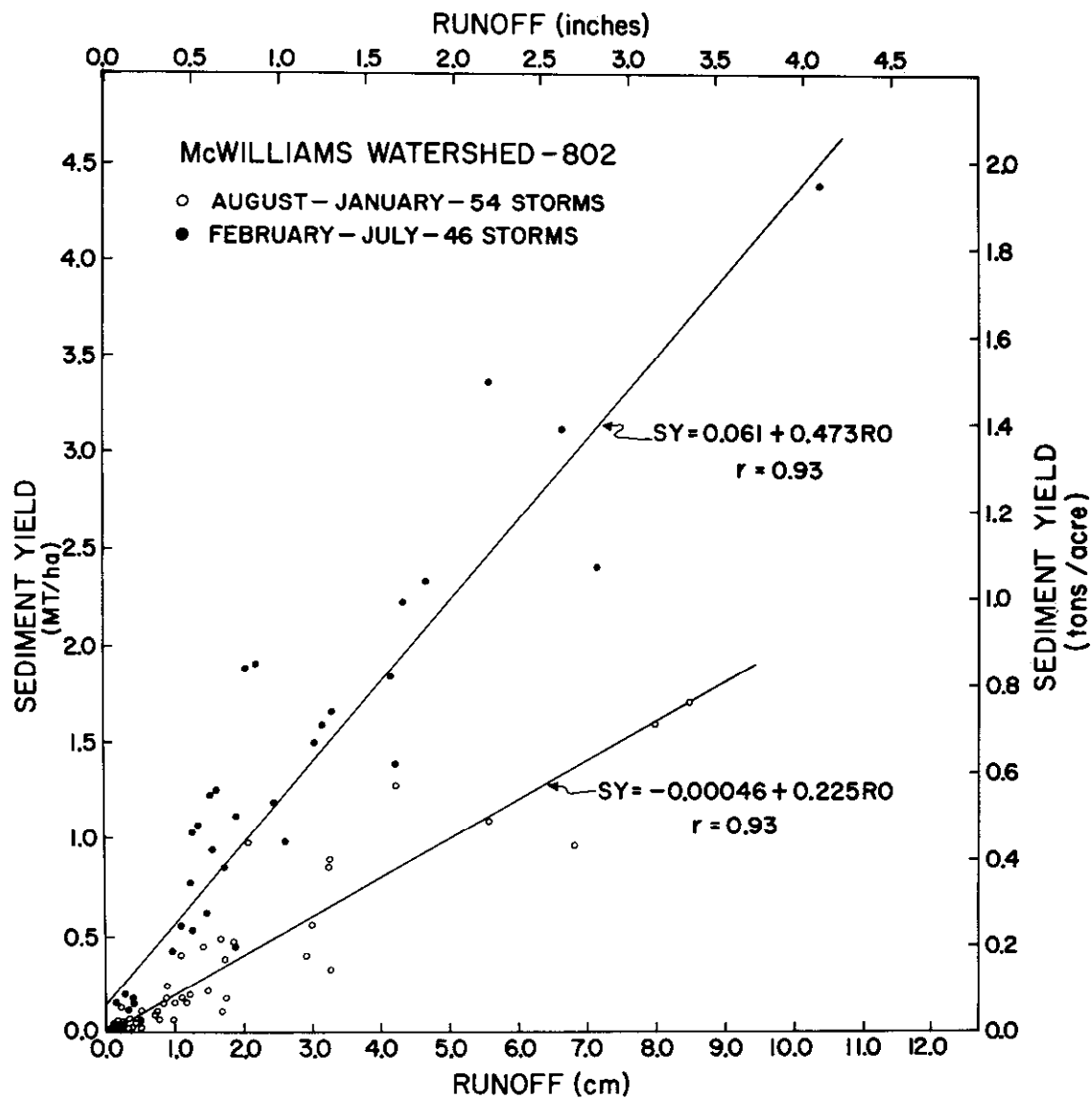


Figure 3--Runoff and Sediment Yield Relationship, McWilliams Watershed 802.

$$SY = -0.00046 + 0.225 RO \quad (1)$$

for the untilled period and

$$SY = 0.061 + 0.473 RO \quad (2)$$

for the tilled period [SY is sediment yield (tons/acre) and RO is runoff (inches)]. The correlation coefficient of the relationship for both periods was 0.93.

The intercepts of both equations are nearly zero, which is to be expected since runoff is necessary for any sediment yield. Thus, the slopes of the equations indicate the relative erodibility of the watershed during the two periods. Sediment yield was about 2.1 times greater when the soil was in the tilled and unprotected condition than from comparable runoff during the untilled, good cover period.

U. S. Weather Bureau records at Clarksdale, MS show the 30-year average rainfall for February through July is 69.14 cm (27.22 inches). This is 55 percent of the long-term average annual rainfall. For the 2 years of record on the McWilliams Watershed, 56 percent of the annual rainfall occurred during February-July and produced 59 percent of the annual runoff and 78 percent of the annual sediment yield. The discharge-weighted mean concentration for February through July was 4560 mg/l compared to 1820 mg/l for August through January. Thus, the mean sediment concentration was about 2.5 times greater during the tilled period.

Above-normal rainfall in March-April 1973 and May-June 1974, when the soil was most vulnerable to erosion (Figure 2), produced sediment yields of 14.28 and 17.80 MT/ha (6.37 and 7.94 tons/acre), respectively. This was about 50 and 61 percent of the annual sediment yield for the 2 years of study. Since rainfall amount greatly affects runoff, and hence sediment yield, as shown in Figures 2 and 3, the yield for each of the water years is probably much higher than the long-term average.

Considering each of the 12 consecutive monthly periods available (Tables 1 and 2) for the 2 years of data on the McWilliams Watershed, only 1 selected year (May 1973 through April 1974) received rainfall close to the 30-year annual average precipitation observed at Clarksdale, MS. Annual rainfall for that period on the watershed was 135.28 cm (53.26 inches), only 8 percent above the 30-year average. This rainfall produced 53.26 cm (20.97 inches) of runoff and a sediment yield of 16.99 MT/ha (7.58 tons/acre). This sediment yield was compared with erosion predicted using the universal soil loss equation (USLE)

$$A = R K L S C P \quad (3)$$

where A is predicted soil loss, R is the rainfall factor, K is the soil erodibility factor, L is the slope-length factor, S is the slope steepness factor, C is the cropping and management factor, and P is the practice factor (Wischmeier and Smith, 1965).

An R-factor of 370 was computed for the selected year (May 1973-April 1974) as defined by Wischmeier (1959). This value is larger than the published value of 330 in Agriculture Handbook 282 because it was computed from greater than normal rainfall rather than for average annual conditions.

The K-factor was determined from the soil erodibility nomograph given in Wischmeier et al. (1971) using entry values of 53 percent silt plus very fine sand, 47 percent clay, 2.5 percent organic matter, blocky structure, and slow permeability. The value of the soil erodibility factor, K, predicted in this manner was 0.29. Using the values of slope length and steepness given earlier, an LS factor of 0.14 was calculated from the slope-length equation (Wischmeier and Smith, 1965). A length exponent of 0.3 was used because the slope steepness was less than 3 percent.

The cropping factor, C, was computed using EI distribution curve No. 22 and Table No. 2 of Agriculture Handbook 282, for continuous cotton; the resulting value was 0.50. Cotton rows on the watershed were up-and-down slope; therefore, the value for the practice factor, P, was one. The resulting soil loss prediction was $(370)(0.29)(0.14)(0.50) = 7.51$ tons/acre or 16.84 metric tons/hectare.

In order to compare this USLE estimate with the measured sediment yield, a delivery ratio (DR) was considered--this recognizes that some of the eroded soil is deposited before reaching the watershed outlet. Although the slope of the V-ditch from the end of the rows to the gaging station was generally less than the row grades of 0.2 percent, little evidence of net deposition was observed. A delivery ratio estimate was computed from

$$DR = \frac{246.56}{454.9(\text{Area})^{0.33852}} \quad (4)$$

(HECTARES)

which was derived by Roehl (1962). Solving the equation for an area of 15.58 hectares, the estimated sediment delivery ratio was 0.97 which agrees with the field observations. By multiplying the erosion prediction by the delivery ratio, a sediment yield of 16.33 MT/ha (7.28 tons/acre) was estimated compared to that measured of 16.99 MT/ha.

SUMMARY AND CONCLUSIONS

Two water years of rainfall, runoff and sediment yield data from a 15.58-ha (38.5-acre) Mississippi Delta watershed, continuously farmed in cotton have been reported. While both years had rainfall amounts 32 and 39 percent above the average annual rainfall for the area and produced abnormally high runoff and sediment yield values (28.8 and 29.1 MT/ha/year), much valuable hydrologic information was gained.

The data indicate that sediment yield is highly dependent on runoff volume for individual storm events. It will be particularly interesting to determine if the runoff-sediment yield relationship will hold for

years of normal and less than normal rainfall. Sediment yield estimated by the universal soil loss equation and a delivery ratio was only 4 percent less than that measured during a 12-month period of slightly higher than normal rainfall. Various people and agencies have had extensive experience using the USLE on slope steepnesses of 3 to 4 percent and greater. The results reported here will allow greater confidence in extending its use on low slopes.

ACKNOWLEDGMENT

We thank the landowner, Mr. G. L. McWilliams, for his cooperation in this research program.

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SEDIMENTATION IN BIRCH LAKE, IOWA COUNTY, WISCONSIN

By

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ABSTRACT

During March 1975, a reservoir sediment survey was made at Birch Lake, latitude 43°00'10" N., and longitude 89°55'10" W., Iowa County, Wisconsin. Twenty-three bottom sediment samples were collected through the ice along eight ranges in the lake. Two ranges were augered on the flood plain of Trout Creek above the impoundment. The samples were first described in the field, and then selected portions of core profiles were analyzed for physical and chemical properties. The volume and density of a 10.5-year accumulation of sediment in the reservoir were determined. The watershed is predominantly cropland and pasture. Land use and land treatment were compared prior to dam construction and in 1974. Comparisons were made between predicted watershed sediment yield and the measured sediment in the reservoir. This study is a basis for future land use, land treatment, and sediment surveys at 5-year intervals.

INTRODUCTION

In 1969, the Soil Conservation Service (SCS), U.S. Department of Agriculture, established a program for making reservoir sedimentation surveys at selected dams designed and constructed with SCS assistance. The program has several purposes: to measure sediment accumulated in small reservoirs of 30,818,700m³ (25,000 acre-feet) capacity or less; to relate land use, changes in land use, and land treatment measures to change in erosion rates; to evaluate quantitatively sources of sediment; to locate high sediment producing areas; to determine the reservoir trap efficiency; and to estimate sediment yield to the reservoir. Periodic measurements are contemplated at 5-year intervals after the initial sediment survey is made. Between 1970 and 1974, five SCS Public Law-566 dams in Wisconsin were permanently range monumented, and resurveys were made to locate range markers and other newly constructed manmade features such as roads and culverts.

In March 1975, a reservoir sediment survey was made at Birch Lake, Iowa County, Wisconsin. The dam at Birch Lake was designed and constructed by SCS for the Iowa County Soil and Water Conservation District and Twin Parks Watershed Association under the authority P.L.-566.

LOCATION

Birch Lake, Iowa County, southwest Wisconsin, has a drainage area of 389 hectares (960 acres). See figure 1. The village of Barneveld is on the southern watershed margin. Barneveld is 69 kilometers (43 miles) west of Madison, Wisconsin, and 23 kilometers (14 miles) east of Dodgeville, Wisconsin.

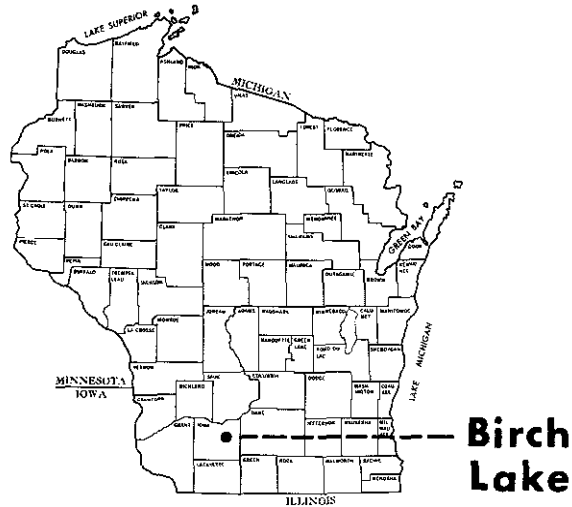


Figure 1. — Location Map

CLIMATE

Iowa County has a humid continental climate with wide extremes of temperature. The coldest month is January with an average temperature of -9° Celsius (16° Fahrenheit). July, the warmest month, has an average temperature of 22° Celsius (72° Fahrenheit). Average rainfall is 81 centimeters (32 inches).

PHYSIOGRAPHY

The watershed is a part of the Upper Mississippi Drainage Basin and is within the Driftless Area of Wisconsin. About 2.4 kilometers (1.5 miles) east of the watershed are two outliers of the Niagara escarpment called the "Blue Mounds" that rise 152 meters (500 feet) higher than the adjacent ridgeland. Some 16 kilometers (10 miles) to the east is the outer Johnstown Moraine of Wisconsin Cary Age. The land form, in late youth or early maturity, is characterized by a few remnants of flat upland and a relatively narrow valley with a steep gradient. The village of Barneveld has an elevation of 376 meters (1,235 feet) and at dam centerline the channel has an elevation of 288 meters (944 feet) mean sea level (m.s.l.). The relief-length ratio is 0.020.

DRAINAGE

Birch Lake dam, on Trout Creek, has headwaters in the Barneveld area at 376 meters (1,235) m.s.l. and drains northwest to enter Mill Creek. Mill Creek joins the Wisconsin River some 29 kilometers (18 miles) downstream from Birch Lake. Trout Creek, a youthful stream having a dendritic drainage pattern, is fed by numerous springs and seeps. The gradient of Trout Creek is 10.5 meters per kilometer (55.7 feet per mile) to its confluence with Mill Creek--a distance of 13 kilometers (7.9 miles).

BIRCH LAKE IMPOUNDMENT

Birch Lake is a roughly rectangular spring-fed impoundment of 4.4 hectares (11 acres) on Trout Creek. The dam was constructed in 1964 as a multiple-purpose reservoir for flood control, sediment storage, swimming, and fishing. The lake is "managed for rainbow trout which are stocked annually to maintain the fishery," (Piening, 1968).

Physical characteristics of Birch Lake:

Length	324	meters	(1,062 feet)
Average width	134	meters	(440 feet)
Area	4.4	hectares	(11 acres)
Length of shoreline	905	meters	(2,970 feet)
Maximum depth	5	meters	(15 feet)
Permanent pool elevation	292	meters	(960 feet) m.s.l.

SOILS AND GEOLOGY

Soils in the watershed are derived from bedrock, residuum, windblown silt, and alluvium. Two percent of the soils are Ashdale silt loam, 2 percent Chaseburg silt loam, 4 percent Lawson silt loam, 5 percent Dodgeville silt loam, 20 percent steep, stony and rocky land, 22 percent a Sogn-Edmund silt loam, and 45 percent New Glarus silt loam. Birch Lake impoundment occupies a 4-hectare (11-acre) tract of Lawson silt loam.

Marine sedimentary rocks of Ordovician age outcrop at and above Birch Lake and are somewhat obscured by Quaternary deposits of soil, colluvium, loess, and alluvium. The oldest exposed formation is the St. Peter sandstone which forms ledges and cliffs. The lower portion of outcrop is frequently covered by partially vegetated to loose sand slopes. The formation is a massive medium-grained quartz sandstone that is nearly horizontal. The formation is about 40 meters (130 feet) thick. Conformably above the St. Peter are fossiliferous shales, sandy dolomites, and dolomites--the Platteville, Decorah, and Galena formations. Thickness of this sequence varies from 67 to 82 meters (220 to 270 feet). Except where slumped or settled, the strata are essentially horizontal. The regional dip of Paleozoic sediments is about 10 feet per mile to the southwest. Bedrock is overlain by varying amounts of Quaternary loess, soils, residuum, alluvium, or colluvium that do not exceed a thickness of 7 meters (22 feet).

AGRICULTURAL HISTORY

In November 1832, Sylvester Sibley, surveyor, mapped the area for the federal land survey program. The scale was "40 chains to the inch," and the only manmade feature of the area was the "Blue Mounds and Dodgeville Road." Survey Volume 43 describes the township and range with comments as "land, rolling; soil, good," "thinly timbered," "some burr-oak timbers," and "brook" (Trout Creek). Three years later, the Military Road was built providing better access to the lead mines and potential farmland. With a decline in lead mining, immigrants of the late 1840's and 1850's settled as farmers. The Civil War brought high values for wheat, dairy products, and beef which encouraged farming. By 1870, dairying became more important than wheat raising. Dairying "received great stimulus through the coming of the Scandinavian and German settlers who were proficient in the care of cattle and intensive farming, and of New Yorker's who were trained as butter and cheesemakers. These settlers led in the establishment of the dairy industry in the rougher areas more profitably pastured than cropped," (Wisconsin Department of Agriculture, 1956). Therefore, in the past 100 years, cropland and grassland have been dominant land uses in the watershed and dairying and livestock products the major agricultural enterprises.

WATERSHED LAND USE 1960 and 1974

Land use in 1960 and 1974 was determined by field reconnaissance, aerial photographs, and farm unit data furnished by former Work Unit Conservationist C. O. Tarrence and present Iowa County District Conservationist G. G. Kinderman of the SCS.

<u>Land Use</u>	<u>1960</u>		<u>1974</u>	
	<u>Hectares</u>	<u>Acres</u>	<u>Hectares</u>	<u>Acres</u>
Cropland	147	362	155	381
Grassland	107	264	72	178
Forest and wildlife	97	240	65	161
Urban and built-up	33	81	33	81
Farm roads and buildings	5	13	5	13
Birch Lake Park	-	-	55	135
Birch Lake	-	-	4	11
TOTAL	<u>389</u>	<u>960</u>	<u>389</u>	<u>960</u>

The comparison of 1960 and 1974 cropland acreages by capability class and percent is as follows:

Capability Class	1960			1974		
	Hectares	Acres	Percent	Hectares	Acres	Percent
Ile2	36	88	24	36	88	23
IIIe2	53	131	36	62	153	40
IVe1	8	20	6	8	20	5
IVe2	50	123	34	49	120	32
TOTAL	147	362	100	155	381	100

Crop rotations are R02H, R03H, and 2R02H with R - corn, O - oats, and H - hay.

Comparative land treatment measures on cropland prior to dam construction in 1960 and in 1974 are as follows:

Practice	1960		1974	
	Hectares	Acres	Hectares	Acres
Up-and-down hill cultivation	25	61	-	-
Cross-slope cultivation	34	84	9	21
Contouring	21	50	13	31
Contour strip cropping	67	164	133	329
TOTAL	147	362	155	381

The park and lake were important additions to recreational facilities. Birch Lake Park is a venture of the village of Barneveld and the Iowa County Soil and Water Conservation District with an easement from the Wisconsin Department of Natural Resources.

PREDICTED GROSS EROSION AND SEDIMENT YIELD

Sedimentation consists of several dynamic processes with highly variable rates. Topography, geology, soils, climate, vegetation, and man are the major determinants of the erosion process. In this watershed, soil losses from agricultural land are quantitatively greater than soil lost by gully, streambank, and roadside erosion. Wind erosion, scour, and streambed erosion are negligible.

In 1960, before dam construction, sediment storage requirements for Birch Lake were determined by field observations, comparisons with similar watersheds, and a predictive equation. About 43 percent of the stream net was walked to record bank erosion and gully. Roadside erosion appeared similar to other watersheds studied in southwestern Wisconsin. Sheet-and-rill erosion from agricultural land was determined by the Musgrave formula suitable for the Corn Belt, (Ghormley, 1956). Soil type, capability class, erodibility, percent and length of slope, and rainfall were used to obtain soil and slope factors. Rotation and management gave a cropping factor.

Soil loss in acre inches per year was determined by multiplying the acreage of a particular capability unit, cropping pattern, and practice with these factors and dividing by 12 to get acre feet. Acre feet were converted to tons and tons per acre. Data was obtained for each farm unit in the watershed during Twin Parks Watershed work plan development in 1960 and again in 1974. For comparability, the Musgrave formula was again used. Table 1 shows the predicted soil loss from gross erosion, sediment delivery ratios, and average annual sediment yield to Birch Lake.

Total deposition in the 50-year period design life was estimated to be 26,222 metric tons (28,904 English tons) with a trap efficiency of 93 percent.

The annual sediment yield from the watershed using 1960 data was predicted to be 1.88 metric tons/ha (0.84 T/AC) and in 1974 predicted to be 1.59 metric tons/ha (0.71 T/AC).

TABLE 1. - PREDICTED AVERAGE ANNUAL SEDIMENT YIELD BY SOURCES - 1960 and 1974

Land Use	1960				1974			
	-----Average Annual Soil Loss - Sheet and Rill Erosion -----							
	metric tons/ha	metric tons	tons/acre	English tons	metric tons/ha	metric tons	tons/acre	English tons
Cropland	13.95	2046	6.23	2255	10.80	1666	4.82	1836
Grassland	0.27	29	0.12	32	0.20	15	0.09	16
Forest	0.27	26	0.12	29	0.22	15	0.10	16
Urban & Built-up	3.36	109	1.50	120	2.24	73	1.00	81
Farm roads & Buildings	11.20	59	5.00	65	11.20	59	5.00	65
Park	---	---	---	---	0.27	15	0.12	16
Birch Lake	---	---	---	---	---	---	---	---
	Total	2269	Total	2501	Total	1843	Total	2030

	Delivery Ratio	Metric Tons Delivered	English Tons Delivered	Delivery Ratio	Metric Tons Delivered	English Tons Delivered
Sheet Erosion - Total	27%	613	674	27%	498	548
Gully and Streambank Erosion	80%	55	61	80%	55	61
Streambed Erosion		Negligible			Negligible	
Floodplain Scour		Negligible			Negligible	
Wind Erosion		Negligible			Negligible	
Total		668	735		553	609

SAMPLING AND ANALYSES

Measurements of sediment thickness were obtained through the ice across eight monumented ranges on Birch Lake and along two flood plain ranges. Seventy-eight measurements were made with a calibrated aluminum sounding pole. Twenty-four undisturbed samples were obtained using a drill rig with a hydraulic piston sampler. Samples were collected in steel tubing 45.7 centimeters (18 inches) long and 7.6 centimeters (3 inches) in diameter. Fourteen soil borings were made by hand along the two Trout Creek flood plain ranges. Figure 2 shows the sediment ranges and location of core samples, pole soundings, and auger borings. Twelve undisturbed samples were extruded and described in the field. One sample was discarded. The remaining cores were extruded in Madison, and 22 samples from 12 cores were analyzed at the Soil and Plant Analysis Laboratory, Department of Soil Science, University of Wisconsin, Madison. Analytic procedures for determining pH, inorganic phosphorus, organic matter and particle size are described in Schulte and Olsen--1970. Results, rounded to whole numbers, are given in table 2. Three samples (1.12, 9.33, and 15.21) were a part of the original Lawson silt loam profile on the flood plain. These show a higher percent of organic matter, a lower pH, and 70 percent or greater silt content.

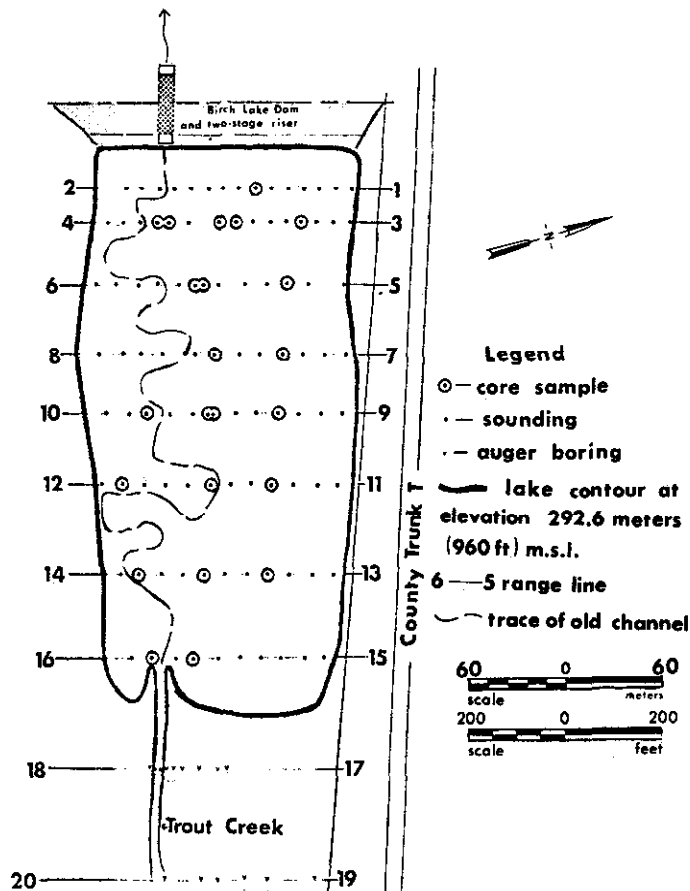


Figure 2. — Birch Lake sediment ranges, and location of core samples, soundings, and auger borings.

TABLE 2. CORE SAMPLE ANALYSES BIRCH LAKE

RANGE	SAMPLE NUMBER	SAMPLE DEPTH	mg/l - P ₂ Inorganic	Percent Or- ganic Matter	pH	Sand Percent	Silt Percent	Clay Percent
1-2	1.11	0-13.97cm. (0-5.5")	195	5	7	37	44	19
	1.12	14.0-38.1cm. (5.5-15")	203	13	6	17	70	13
5-6	5.21	0-10.2cm. (0-4")	180	4	8	29	54	17
	5.22	10.2-17.8 cm. (4-7")	162	3	8	51	40	09
	5.23	17.8-24.1 cm. (7-9.5")	150	3	8	55	36	09
7-8	7.11	0-17.8 cm. (0-7")	195	3	8	19	70	11
	7.12	17.8cm-25.4 (7"-10")	165	2	8	07	80	13
	7.21	0-43.2cm. (0-17")	196	1	8			
9-10	9.21	0-15.2cm. (0-6")	144	3	8	17	70	13
	9.22	20.3-39.4cm. (8-15.5")	113	1	8	19	67	14
	9.31	0-16.5cm. (0-6.5")	117	2	7	85	11	04
	9.32	16.5-34.3cm. (6.5-13.5")	141	2	7	37	52	11
	9.33	34.3-45.7 (13.5-18")	173	9	6	11	82	07
11-12	11.11	7.6-16.5 cm. (3-6.5")	195	3	8	43	51	06
	11.12	16.5-43.2 cm. (6.5-17")	225	2	7			
	11.21	7.4-8.9 cm. (2.9-3.5")	177	3	8	37	52	11
13-14	13.12	0-20.3 cm. (0-8")	201	5	7	47	38	15
15-16	15.11	0-40.6 cm. (0-16")	293	3	7	14	74	12
	15.12	40.6-50.8 cm. (16-20")	233	4	8	48	36	16
	15.21	50.8-76.2 cm. (20-30")	101	26	6	14	72	14
	15.31	0-20.3 cm. (0-8")	174	3	8	28	60	12
	15.33	20.3-45.7 cm. (8-18")	144	4	8	54	42	04

THICKNESS AND DISTRIBUTION OF BOTTOM SEDIMENTS

The thickness of bottom sediment deposits ranged from 12.7 centimeters (5 inches) to a maximum of 66.0 centimeters (26 inches). Range 1-2 had deposits with an average thickness of 20.3 centimeters (8 inches). The thickest deposits were near the upper end of the lake and had an average thickness of 48.3 centimeters (19 inches). See figure 3 for sediment distribution profiles. End area accumulation shows the same variation with 36.1m² (388.8 ft²) of sediment along Range 1-2 and 67.7m² (723.2 ft²) of sediment along Range 15-16. Variation in sediment thickness was found on every range. These differences are in part due to irregular pre-deposition topography, the gradual filling of the original channel, meander scars, low stream terraces, and manmade excavations contributed to non-uniform distribution of sediment. Nearshore slumps, abutment slope wash, and intermittent contributions of sediment from culverts have created additional micro-relief.

Trout Creek is building a delta 5 to 9 meters wide (15 to 30 feet) which extends about 38 meters (125 feet) into the lake. Natural levees, just above water level, have formed along the sides of the channel for a distance of 18 meters (60 feet) into the lake. The deltaic deposits are silty sands.

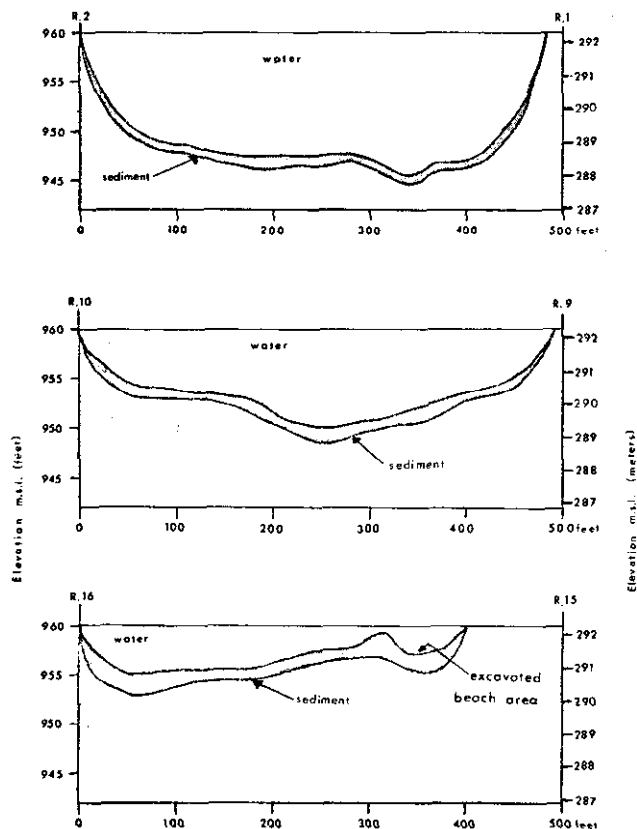


Figure 3. — Sediment distribution along ranges
near outlet (R.1-2), middle (R.9-10),
and near inlet (R.15-16).

DENSITY AND COMPOSITION OF BOTTOM SEDIMENTS

The specific weight of deposited sediments was computed from core samples of known volume that were oven-dried and weighed. The 24 samples ranged from 0.79 g/cc (49 lbs./ft³) to 1.36 g/cc (85 lbs./ft³). Because of variation in organic content and/or particle size distribution, several cores were later divided into smaller units. These partial samples had more variation in weight per unit volume, with a low density of 0.26 g/cc (16 lbs./ft³) in organic silts, to a high of 1.52 g/cc (95 lbs./ft³) in silty quartz sands. An average density for the reservoir sediment is 1.11 g/cc (69 lbs./ft³). Composition of reservoir sediments averaged 34 percent sand, 52 percent silt, and 11 percent clay. Sand ranged from 7 to 85 percent; silt ranged from 11 to 82 percent; and percent of clay ranged between 4 and 19 percent. Using analyses from soil surveys, the weighted average A-horizon of Chaseburg, Dodgeville, Ashdale, Lawson, New Glarus, and Sogn-Edwards soils was 88 percent silt and clay, and 12 percent sand. St. Peter sand from a colluvial slope near the dam was 82 percent sand and 18 percent silt and clay. Slope-washed sediment from a road bank on county trunk T was 80 percent silt and clay and 20 percent sand. Sand from outcrops of St. Peter sandstone, a greater sand content in the subsoil and parent material, and sand added to the beach and swimming area account

for the additional amount of reservoir sand. Trap efficiency is also higher for sands.

In terms of general sediment distribution, there is no significantly higher sand concentration in any part of the reservoir except for the delta of Trout Creek and the swimming area. During construction, the channel of Trout Creek within the pool area was partially backfilled to the top of the bank. The small reservoir size, turbidity currents, and other hydraulic complexities may account for this finding.

SEDIMENT AND STORAGE VOLUMES

Table 3 gives the original "as built" storage capacity allocations in Birch Lake.

TABLE 3 - AS BUILT RESERVOIR STORAGE ALLOCATIONS

Storage	hectar-m.	acre-ft.	WS cm	WS inches	Elevation m.s.l.	
					m.	ft.
Sediment	1.7	13.5	0.429	0.169	290.2	952.0
Permanent Pool	7.9	64.1	2.032	0.800	292.7	960.0
Floodwater Retention *	17.5	142.0	4.509	1.775	295.1	967.8
TOTAL STORAGE	27.1	219.6	7.070	2.744	-	-

*To high stage inlet on riser which is equivalent to emergency spillway storage. The top of dam is at elevation 296.1 meters (971.3 feet) m.s.l.

Sediment accumulation was computed by two methods: range line with modified Dobson prismoidal formula and range line method using planimetered average end areas. Volume of sediment accumulated by each method is as follows:

Dobson prismoidal 12,056m³ . . . (9.77 acre-feet)

Planimetered end areas 13,191m³ . . . (10.69 acre-feet)

The two methods seem comparable in accuracy and give an average volume of 1.2 hectare-m (10.23 acre-feet) of sediment in Birch Lake. The reservoir, which has been receiving sediment for 10.5 years, has a design life of 50 years.

Total deposition in 10.5 years determined by the 1975 reservoir sediment survey was 13,949 metric tons (15,376 English tons) as compared with a

predicted deposition of 5,507 metric tons (6,070 English tons) in the same period of time and computed prior to dam construction.

The reasons for this difference are numerous and varied. They include above average yearly precipitation for several years, high erosion rates from borrow areas within the reservoir, and almost annual replenishment of beach and swimming area sands (35 tons average annual). Location of the damsite in non-resistant quartz sandstones above which are less erosive calcitic-dolomites gives a steep gradient above site. The gradient flattens rapidly in the area of the reservoir with consequent deposition. During the planning stage of Twin Parks Watershed which terminated in March 1961 with a published work plan, storage requirements were less precise than those developed in April 1963 for a final design. In addition a supplemental watershed work plan was issued in March 1963 when the sponsoring organization requested that the damsite plan be revised to include a recreation pool. This added more storage to the reservoir and increased trap efficiency by 3 or 4 percent.

Most illustrative of non-straightline sediment accumulation, or average annual amount of sediment entrapped in a reservoir, is the variation in amount and intensity of rainfall. A daily rainfall record is available for Blue Mounds, 2.4 kilometers (1.5 miles) east of Birch Lake. Daily records have been kept since 1963. From 1964 through 1974 there was above average precipitation in 1965, 1968, 1972, 1973, and 1974, ranging from 15.37 centimeters (6.05 inches) in 1973 to, 20.37 centimeters (8.02 inches) in 1965. Ten 24-hour rains exceeded 5.08 centimeters (2.00 inches). On July 14, 1966, there was a rainfall of 11.07 centimeters (4.32 inches) in a 24-hour period. On June 21, 1974, a rainfall of 9.78 centimeters (3.85 inches) occurred within a 24-hour period. The former was slightly higher than a 10-year frequency event, and the latter slightly more than a 5-year 24-hour frequency.

SUMMARY AND CONCLUSIONS

Basic data compiled from the Birch Lake study will be quite useful in determining sediment yield and storage needs of dams in southwest Wisconsin areas that are predominantly cropland and pasture.

The 1975 sediment survey indicated an average annual sediment yield in 10.5 years of 3.45 metric tons/ha (1.54 tons/acre) as compared with a predicted average annual yield of 1.88 metric tons/ha (0.84 tons/acre) in 1960 prior to dam construction and 1.59 metric tons/ha (0.71 tons/acre) in 1974.

Sediment in the reservoir is thickest near the inlet of Trout Creek with an average thickness of 48.3 centimeters (19 inches). At the dam the sediment averaged 20.3 centimeters (8 inches) in thickness. Bottom sediments have an average composition of 34 percent sand, 52 percent silt, and 11 percent clay. The sand is in the fine to very fine size grades of quartz grains. Organic matter in the sediment profile varies from 1 to 5 percent averaging 3 percent. All ranges but 15-16 decrease in organic matter with depth, suggesting an initial and rapid accumulation of sediment after dam

closure from normal sources and borrow areas, culvert discharges, slope wash and normal decomposition of vegetation. The southern portion of range 15-16 is near marsh with a luxurious growth of emergent vegetation and algae. The predicted volume weight of submerged sediment was 0.10 g/cc (65 lbs./ft³) and an analysis of 24 bottom sediment samples averaged 0.11 g/cc (69 lbs./ft³). The difference between the predicted and actual sediment accumulation is probably due to underestimating the amount of sand reaching the lake from the terrain through which Trout Creek flowed.

Fifteen bottom sediment samples were mildly alkaline, three were neutral, and two samples were moderately alkaline. In contrast, unlimed upland soils are slightly or medium acid. The results of liming the plow layer are well demonstrated by deposited sediment.

Source materials of reservoir sediment are a combination of soil, subsoil, loess, weathered and slope washed Ordovician marine sediments, clay-chert residuum, alluvium, and colluvium. In addition to normal geologic erosion, and quantitatively of much greater significance, are the activities of man in his farming processes. Sheet-and-rill erosion from cropland is probably the largest source of sediment delivered to Birch Lake.

It is suggested that there were several short term sediment contributions to the reservoir. No data is available for a quantitative evaluation. During dam construction, borrow areas adjacent to the dam or within the pool area were unvegetated. These areas had both high erosion and sediment yield rates. We can assume an erosion rate of between 134-157 metric tons/ha (60-70 tons/acre) and a delivery rate of 90 to 100 percent. Occasionally high water covers the beach area after storms and when the water recedes a silt layer remains. This makes the beach undesirable for sunbathing or swimming. Additional sand is added to the beach. In the smoothing and mixing process, some of the sediment is raked into the lake.

High soil losses from cropland are directly related to the raising of row crops in a dairy-livestock economy on steep class IVe lands. This is particularly true of watersheds in the Driftless Area of southwest Wisconsin. In 1960, 6 percent of the watershed cropland--8 hectares (20 acres)--was Class IVe1, and 34 percent of the cropland--50 hectares (123 acres)--was Class IVe2. By 1974, there was no reduction in Class IVe1 cropland, and only three acres less Class IVe2 cropland. Class IV land has severe limitations and requires very careful management. In order to reduce gross erosion in the watershed and sediment yield to the lake, cooperators with the Iowa County Soil and Water Conservation District should be encouraged to divert their Class IV cropland to pasture and/or woodland. This goal can be accomplished by a change in rotations and management practices on the remaining cropland. As of December 1974, five Iowa County SWCD cooperators owned 287.6 hectares (710 acres) and four non-cooperators owned 101.2 hectares (250 acres). Before the 1980 resurvey of Birch Lake, it is hopefully anticipated that landowners will reduce the amount of Class IV land being cropped and extend additional soil-conserving land management practices to all cropland.

For an accurate determination of gross erosion and sediment yield to impoundments in similar agricultural, climatic, geographic, and geologic settings, there is no substitute for one or more reservoir surveys of manmade lakes in the region. Volumetric determinations, sediment analyses, and data-gathering for land use, agricultural practices, and sediment sources are necessities.

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SEDIMENT YIELD FROM STEEP LANDS IN THE DRIFTLESS AREA

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ABSTRACT

Suspended sediment in runoff water was measured on natural runoff plots and small watersheds in different land uses on southwestern Wisconsin's ridge and valley lands. Substantial amounts of sediment were discharged only from cultivated or heavily grazed catchments. The greatest amounts--sometimes exceeding 200,000 ppm--came from tilled cropland in early stages of crop development. Values varied greatly from one catchment to another, probably because of differences in erosion patterns that developed under tillage and because of differences in cover density.

Ungrazed forest and prairie in the Driftless Area yield no significant amounts of runoff or sediment, regardless of slope steepness, unless they intercept water from overlying fields. However, field runoff can carve huge gullies on forested slopes that lie below cultivated uplands. Thus, the forested slopes of the area have been a major sediment source from gully erosion since the time of agricultural settlement.

INTRODUCTION

Floods, erosion, and muddy streams are major resource problems in the unglaciated or "Driftless Area" of Wisconsin, Minnesota, and Iowa. They result from farming erosive loessal soils on steep slopes. The present paper summarizes the data from 4 years of measuring suspended sediment on small experimental catchments and presents some additional observations on sediment movement from 15 years of research on the hydrology of small Driftless Area watersheds.

THE AREA AND ITS BASIC HYDROLOGY

The area is a 25,000 km² (10,000 mi²) relict of the preglacial landscape. The terrain is highly dissected with steep, wooded slopes separating flat or gently rounded ridges from narrow valleys, or "coulees." Ridgetops lie up to 120 m (400 ft) above the valleys. Forests of oak, hickory, and associated mesophytic species normally occupy only the steeper slopes, sandwiched between two levels of farmland.

The soils are predominantly loessal silt loams and range in depth from a few centimeters to more than 5 m (15 ft). The geology is simple. Ridges are capped with dolomite with underlying layers of sandstone. Both the caprock and the various sandstone formations are horizontally bedded and permeable. Thus, rain that falls on top of a ridge may eventually percolate to the valley water table 125 m (410 ft) down.

The climate is midcontinental with hot summers and long, cold winters. Annual precipitation is about 800 mm (32 in), two-thirds of which falls from May through September, much of it as high-intensity convection storms. The steep, unglaciated terrain, and a peculiar land use pattern give the region a distinctive hydrology. The variable source area concept of runoff as described by Hewlett and Hibbert (1967) for mountain watersheds in the East does not appear to apply here. Watersheds smaller than 250 ha (1 mi²) normally have no perennial streams. Because of practically unlimited water storage opportunity in the soil and rock mass, water flows from the land surface only when rainfall or snowmelt exceeds the infiltration rate or the percolation rate of a saturated subsurface layer. Thus land use greatly influences runoff and sediment movement in the area.

Convection storms are the usual cause of summer floods but their occurrence on any one watershed is erratic and unpredictable. Some years none occur; in others, a whole series may occur in quick succession. Most Driftless Area streams flood to a certain extent every spring. However, because they are caused by frozen ground overland flow, spring floods carry less sediment than summer floods.

PAST WORK

Previous reports stressed the need for agricultural conservation practices (Hays, McCall, and Bell, 1949), and the importance of land use on runoff (Sartz, 1963; 1969; 1970). Rainfall intensity is the one single factor most related to overland flow. Prolonged, heavy storms may produce little overland flow and sediment if intensities are not high (Hays et al., 1949; Sartz, 1970).

Tilled cropland is by far the greatest source of flood runoff and stream sediment, particularly from summer storms. Runoff from tilled land may be 10 times greater than from hay and pastureland, and soil loss may be 100 times greater. Although hayland produces much less runoff than tilled land, it is a source of rainfall runoff during heavy storms and of snowmelt runoff when the ground is frozen. Pastureland may produce more or less runoff than hayland, depending on the grazing intensity. Runoff from forest land is minimal, regardless of the slope and condition of the forest (Sartz, 1970).

STUDY METHODS

Overland flow from small, single-use catchments was measured for 10 years and suspended sediment in the runoff water for 4 years. The catchments are all on the Coulee Experimental Forest, a 1,200 ha (3,000 acre) area of mixed open land and forest near La Crosse, Wisconsin. Land uses studied included uncut, logged, and grazed forest; hayland (alfalfa meadow); tilled cropland; old field; open-land pasture; and goat prairie (shallow-soiled areas with sparse herbaceous cover and rock-strewn surface).

The Experimental Catchments

The forested catchments are single, ridge-to-valley topographic units with sharp divides. Of five forested catchments studied, four were relatively undisturbed at the beginning of the experiment and one was grazed. The grazed catchment has a parklike forest cover with some patches of goat prairie. It is traversed by a tractor road, that contributes to overland flow. The area was used as cattle pasture for many years, and because of the poor condition of the forest, the amount of exposed soil, and obvious signs of overland flow, it is an extreme example of heavily grazed forest.

The meadow, tilled cropland, and old field catchments are segments of ridgetop fields that lie above forested slopes. The segments are bounded by natural divides on the sides and top but were terraced at the bottom to cut off downslope runoff and channel it to a flume. The terraces trapped some sediment; so the amount that moved through the flumes was less than the amount that washed from the land. Because of their small size and the artificial terraces, these catchments might better be described as natural runoff plots. Five of the open-land catchments were in corn or oats for 5 consecutive years and were then seeded to alfalfa meadow. Hayland was usually cropped twice a year. The old field catchments had been cropped and pastured for many years until 1960.

Open pasture runoff was measured on two pairs of adjacent catchments. One pair was the primary pasture for a dairy herd and was heavily grazed throughout the growing season. The other pair was used only as supplemental pasture and was not grazed until late in the summer. The land use, number, size, and slope of the catchments are given in table 1.

Table 1.--The number, size range, and average slope of the catchments

Land use	: Number	: Size range (Hectares)	: Average slope (Percent)
Tilled	5	0.7-1.1	15
Meadow	¹ 2-8	0.7-1.3	15
Old field	¹ 1-3	0.3-0.6	15
Open pasture	4	2.3-2.7	25
Forest pasture	1	7.3	35
Undisturbed forest	¹ 3-4	15.5	35
Logged forest	1	16.0-25.0	35
Goat-prairie	1	0.5	50

¹The number varied over the years of study.

Four dual-use catchments were also studied. These are made up of forested slopes rimmed by a segment of open land at the top. The open uplands rim the catchments in a rough contour belt that averages about 100 m (300 ft) wide on a slope of about 15%. Gullies carved by overland flow from the

fields slash the forested portions from top to bottom. Further description of these catchments was given by Sartz (1971).

Runoff And Sediment Measurements

Runoff was measured with H- or San Dimas flumes and water-level recorders equipped with automatic trips. Suspended sediment was sampled with stage samplers as described by Sartz and Curtis (1967) (fig. 1). The stages were as follows:

46 cm H-Flume 61 cm H-Flume 61 cm San Dimas Flume

(In liters per second)

0.6	0.7	13.9
2.0	2.4	39.9
19.0	21.1	185.8
59.2	63.7	385.1
	160.0	682.4



Figure 1.--Stage sampler on 46-cm H-flume with housing cover open (513781).

Because the "one-shot" samples collected by the stage sampler were only of the rising stage, they did not permit accurate estimates of total sediment discharge. However, they did provide a means of estimating comparative discharge from the different land uses.

Sediment content was determined by drying and weighing and was expressed as the ratio of dry sediment weight to total sample weight, in parts per million.

Data Analysis

Because of the erratic nature of soil detachment and sediment movement, sediment data at best give only gross estimates of the true sediment discharge. Although sediment content of the water is normally related to stage of flow, it is also known to be higher at rising stages than at falling stages. Thus, estimating total sediment discharge with any kind of precision requires proportionate sampling over the total range of flow.

Because our samples came essentially from the rising stage only, and were limited to not more than four or five samples per discharge event, I could not justify computing total sediment discharge by summing the values for each stage. I, therefore, chose to simply compute mean sediment contents, using all stages for a given catchment and flow event. I also computed means (for both runoff and sediment) for a given land use where we had records from two or more catchments in the same land use. Thus, table values, unless otherwise stated, were derived from mean sediment rates for all stages and mean sediment and water discharges for one or more catchments. Sediment discharges per unit of land (tables 2 and 3) were computed to allow comparison with results from other places. However, these data should be used with caution because of the limitations imposed by the sampling method.

Table 2.--Annual runoff and sediment discharge, 1964-1967

Land use	Runoff				Sediment			
	: 1964	: 1965	: 1966	: 1967	: 1964	: 1965	: 1966	: 1967
		(Millimeters)				(Metric tons per hectare)		
Tilled cropland	31.90	151.97	130.35	-	4.601	80.600	.690	-
Hayland	.76	32.00	9.73	22.40	.002	.081	.004	.029
Open pasture								
(Heavily grazed)	11.89	49.86	(²)	22.35	.520	3.501	.412	.242
Open pasture								
(Lightly grazed)	(²)	16.08	(²)	14.35	(²)	.047	(²)	.069
Old field	.03	14.10	.28	19.46	.0	.004	.0	.047
Forest pasture								
(Heavily grazed)	.0	7.65	.10	(²)	.0	.616	.002	.139

¹The catchments were in first-year meadow, but still produced large amounts of runoff and sediment because of extensive rilling in 1965.

²Record incomplete.

Table 3.--Runoff and sediment discharge from individual ungrazed forested catchments for two storms

Storm date and amount	Runoff				Sediment ¹			
	Unlogged		Logged		Unlogged		Logged	
	catchments		catchment		catchments		catchment	
	T ₁	T ₂	T ₃	T ₆	T ₂	T ₃	T ₆	
	(Millimeters)				(Metric tons per hectare)			
June 15, 1967 (107 mm)	0.60	2.62	0.25	3.61	0.0435	0.0025	0.0116	
June 21, 1968 (102 mm)	.00	.33	.02	.87	.0002	.0000	.0141	

¹Sediment was not measured on T₁ catchment.

RESULTS

Although the relation between discharge stage and sediment content was not evident from individual storm values, it became evident when the data from all storms were pooled, especially at the higher stages for high sediment-producing land uses (fig. 2).

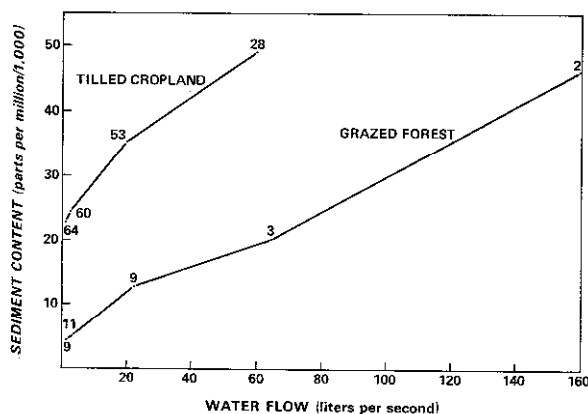


Figure 2.--Relationship between water flow and sediment content for tilled cropland and grazed forest. The tilled cropland values are means from five catchments, the grazed forest values, means from one catchment. Numbers show the number of sediment samples at each point.

Substantial amounts of sediment were discharged only from cultivated or heavily grazed catchments (table 2). As expected, the greatest amounts came from tilled cropland in early stages of crop development when the soil surface was essentially bare. Amounts in individual sediment samples

sometimes exceeded 200,000 ppm. Maximum amounts measured for the various land uses were:

	<u>ppm</u>
Tilled cropland	238,000
Open pasture (heavily grazed)	82,000
Forest pasture (heavily grazed)	55,900
Open pasture (lightly grazed)	13,000
Hayland	19,800
Old field	300
Logged forest	3,600
Undisturbed forest	100

Values varied greatly from one catchment to another, probably because of differences in erosion patterns that developed under tillage and because of differences in storm rainfall and cover density.

Just a few storms each year accounted for most of the sediment. For example, in 1965, a year of many runoff-producing storms, two storms within 5 days--May 21 and May 25-26--produced 93 percent of the year's sediment yield from cropland catchments. The May 25-26 storm alone produced 78 percent. Both rains fell on almost bare soil. The catchments had been seeded to oats about 3 weeks before the storm and the newly emerged oat seedlings offered little soil protection. Furthermore, rill patterns had already developed on the land from four smaller storms in the preceding 10-day period.

None of the four ungrazed, forested catchments or the goat-prairie catchment produced measurable flows during this period. In fact, only two storms (both exceeding 100 mm of rain) during a 13-year period of record produced measurable flow from these catchments. Based on this record, mean annual flow from undisturbed forest was 0.1 mm (0.004 in.) and mean annual sediment discharge was 0.0002 metric tons per ha (0.0001 tons/acre).

Logging had some effect on both runoff and sediment movement. One of the four forested catchments was logged (two-thirds of the area was clearcut) in the fall of 1966 after a 5-year period of no flow. Large storms on June 15, 1967 (107 mm), and June 21, 1968 (102 mm), produced more flow from this catchment than from the other ungrazed forested catchments (table 3). However, it has yielded no flow since June 1969.

Dual-use catchments (open land on the ridgetop, forest land below) generally yielded more sediment than the contributing open land (table 4). This was not surprising. We have seen muddy water flowing through lower station flumes when upland runoff (from snowmelt) was clear. Apparently the water picks up sediment deposited by earlier, smaller flows--or by bank sloughing--as it flows through the steep, eroded channels of the forest zone.

Table 4.--Mean sediment content at upper and lower stations
on dual use watersheds C2 and C3
(In parts per million/100)

Date of storm	C2		C3	
	Upper	Lower	Upper	Lower
May 21, 1965	1,667	1,969	716	918
May 25, 1965	1,956	1,392	818	1,406
July 9, 1965	232	431	80	432
August 14, 1965	40	205	36	83
August 17, 1965	58	129	22	86
August 27-28, 1965	24	59	11	97
June 9, 1967	103	375	46	1,800
Average	583	651	247	689

DISCUSSION

Tilled cropland was by far the most important source of sediment, and most of it was produced by a few storms each year, usually high intensity rains falling on bare soil. Sediment movement from hayland, lightly grazed pasture, and old field was minimal. Heavy grazing increases runoff and sediment yield to the extent that animal traffic bares the soil. One heavily grazed catchment produced more runoff and sediment than the other because it had a gully above the flume. The forest pasture, although heavily grazed, produced more runoff and sediment than would have been normal because of a tractor road through the catchment. Cessation of grazing brings rapid reduction in runoff, however, with a corresponding reduction in sediment discharge (Sartz and Tolsted, 1974). Ungrazed forest--and even clearcut forest--produced insignificant amounts of sediment, even when heavy rains did produce some runoff.

Although the forests are not a source of floods, they have yielded a large part of the sediment carried by floodwaters over the years. This is the result of the distinctive Driftless Area land use pattern. A 1963 survey on the Coulee Experimental Forest showed that gullies slash the slopes wherever ridgetop fields have dumped water into the woods. Gully systems on wooded slopes often show dendritic or branching patterns where runoff water from large fields runs into the woods at many different points (fig. 3). Although many of the gullies were formed years ago, some are recent (fig. 4). The bouldery outwash fan is locally known as a rock or limestone run. Often they cover roads or clog culverts and bridges. The gullies and the debris that accumulates in them between storms that flush them out are a source of substantial quantities of both suspended sediment and bedload material in the area's streams. Thus, soil conservation practices that reduce runoff and erosion from farm fields would also reduce the sediment contribution from the wooded slopes below.



Figure 3.--Gully on wooded slope below open land, Coulee Experimental Forest. Note man holding rod (lower left) (504138).

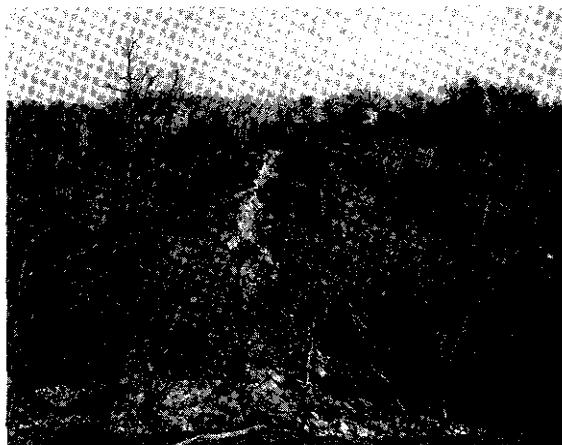


Figure 4.--Woodland gully with rock outwash fan at base. This was caused by one storm in 1960. Runoff was from a small field on top of the ridge (500517).

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RELATION OF EROSION TO SEDIMENT YIELD

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ABSTRACT

Sediment yield is dependent on the gross erosion in the drainage basin and the transport efficiency of the channel network. Stream channel characteristics, diversity in landforms, and flood-plain development all are important factors in determining conveyance, or sediment delivery to downstream points.

Qualitative evaluation was made of sediment conveyance, on a scale of zero to one for Ryan Gulch basin, northwestern Colorado. The presence of alluvial fans, dams and irrigation works, headcuts and ungullied reaches of valley floor and general channel condition were considered. An average conveyance for the basin was computed by weighting ratings of individual reaches. The estimated conveyance for the whole basin indicates that only a very small part of the eroded material is presently being transported through the system.

INTRODUCTION

The relation of erosion on an upland site to sediment yield at a measurement point somewhere downstream in the drainage network has been the subject of considerable research in the past three decades. Progress in recent years has resulted in a better understanding of erosion processes and methodologies for routing the products of erosion through a drainage system. An ultimate goal, however, is a predictive sediment-yield model that is based on physical processes. Empirical relations, such as sediment-delivery ratios derived from data on small basins, do not satisfactorily explain the processes. If it is assumed that a part of the eroded material accumulates as coluvium and flood-plain deposits then the concept of equilibrium in sediment transport cannot be valid. The storage of sediment enroute in the system must fluctuate with changes in land use, conveyance efficiency of channels, and climatic conditions. This is especially true in the arid and semi-arid environments of the western United States. The vegetation cover is generally sparse and the percent of bare soil exposed to erosion by raindrop impact or overland flow is, therefore, very high. Also, the high-intensity thunderstorms that produce most of the runoff in the ephemeral stream channels are generally localized and only a small part of a drainage system is affected by a single storm event. As the stream-flow continues beyond the storm area, sediment-laden runoff is absorbed by the dry channels resulting in deposition of sediment loads.

The common relation shown by most studies of sediment yield is a decrease in unit sediment yield as well as unit runoff with increase in drainage area. An example of this is a study of 99 small basins in eastern Wyoming (Hadley, 1961). Figure 1 shows the data for sediment

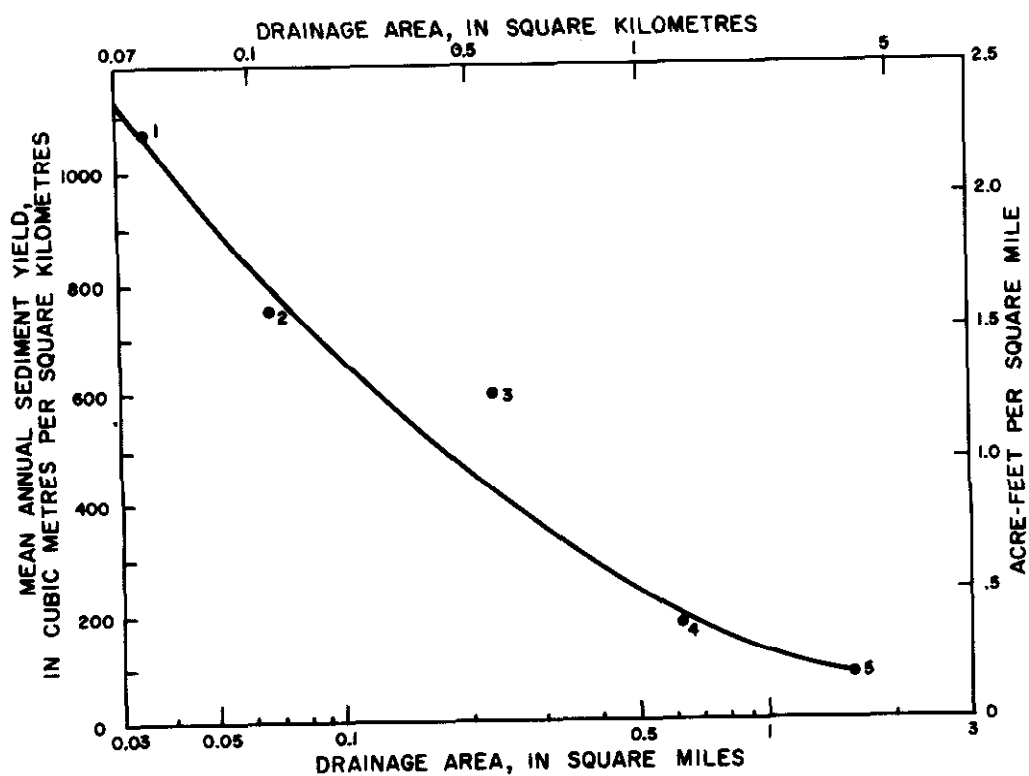


Figure 1.--Relation of mean annual sediment yield to drainage area by size class for 99 small basins in eastern Wyoming. Size classes in km^2 are as follows: 1 (<0.13), 2 (.14 to .25), 3 (.26 to 1.3), 4 (1.4 to 2.6), and 5 (>2.6).

yield from the 99 basins divided into five groups ranging from less than 0.13 km^2 (0.05 mi^2) to about 5 km^2 (2 mi^2). Sediment yield decreases from $1,140 \text{ m}^3$ per km^2 (2.4 acre-ft per mi^2) at $.07 \text{ km}^2$ (0.03 mi^2) to $95 \text{ m}^3/\text{km}^2$ (0.2 acre-ft per mi^2) at about 5 km^2 (2 mi^2). The data shown for the 99 basins represent the total sediment yield inasmuch as the points of measurement are reservoirs that trapped virtually all of the eroded material from the contributing drainage areas. In order to illustrate the interaction of processes that are responsible for this decrease in sediment yield, data from a basin in northwestern Colorado, that of Ryan Gulch in the Piceance Basin, are used in this paper to route the sediment through the drainage network in a qualitative way.

Example Case

The Piceance basin in northwestern Colorado contains many tributary sub-basins 2.6 to 5.2 km^2 (1 or 2 mi^2) in area, where significant amounts of sediment are discharged, but only small amounts of sediment are discharged from larger tributary drainage areas. This is caused by the loss of transport capability when flows are absorbed into the coarse material on alluvial fans, flood plains, and ephemeral stream channels. Ryan Gulch basin is used to illustrate these transport processes.

Basin characteristics

Ryan Gulch is an ephemeral stream, which is tributary to Piceance Creek. Its drainage basin is about 26.4 km (16.5 mi) in length and averages about 4.8 km (3 mi) in width, and has an area of 124.8 km^2 (48 mi^2). The altitude along the drainage divide of Ryan Gulch basin is about $2,621 \text{ m}$ ($8,600 \text{ feet}$), and the altitude at the mouth is about $1,859 \text{ m}$ ($6,100 \text{ feet}$); the average valley gradient is 2.9 percent. Annual precipitation ranges from about 330 mm (13 inches) in the lower part of the basin to about 508 mm (20 inches) in the upper part. About 60 percent of the precipitation occurs as snow during the period October through April. The soils of the uplands are stony sandy loams and stony silt loams derived from sandstones and marlstones of the Tertiary Uintah formation. A moderately dense plant cover of big sagebrush, mountain shrubs and grass understory exists in the upper half of the basin, and a sparse to moderate cover of big sagebrush and pinyon-juniper exists in the lower half of the basin. The bottomlands are covered with moderately dense stands of big sagebrush and rabbitbrush.

Annual runoff from the hillslopes is low with some occurring from melting snow, but the largest flows occur as the result of intense summer thunderstorms. Estimates of annual source-area sediment yield were made for watershed areas having third- and fourth-order channels (based on interpretation of $1:12,000$ scale aerial photographs and using the Strahler, (1952) method for ordering channels) (Frickel, 1975). These estimates range from 50 to $380 \text{ m}^3/\text{km}^2$ (0 to 0.8 acre-ft per mi^2) in the upper 35 percent of the basin and from 240 to $710 \text{ m}^3/\text{km}^2$ (0.5 to 1.5 acre-ft per mi^2) in the lower 65 percent of the basin.

Much of the sediment transported in the Ryan Gulch basin is derived from the rilling of hillslopes with moderate to steep gradients. Some sediment also is contributed by headcuts in the valley alluvium and in alluvial fans and by lateral migration of gullies across the valley floors.

Tributary channels--Figures 2 and 3 show an aerial photograph and map of a reach of the Ryan Gulch basin from about .8 km (one-half mile) to 2.4 km (1½ miles) upstream from the mouth. This reach, which is typical of many of the tributaries of Piceance Creek, contains excellent examples of the relation between channel morphology and sediment transport.

Twenty-five percent of the principal (third and fourth order) tributaries to Ryan Gulch are incised to the main channel as shown at Point A in figure 2. Sediment transport to the main valley is efficient and the channel would be assigned a relative sediment-delivery factor of 1.0 using the scheme shown in table 1, which was adapted from Frickel (1975). The remaining 75 percent of the tributaries are gullies that

Table 1.--Guidelines for evaluating relative sediment delivery in the Ryan Gulch basin, northwestern Colorado, modified from Frickel, (1975)

Relative sediment delivery	Channel conditions
1.0	Unvegetated gullies with no deposition
0.75	Unvegetated gullies with sediment deposits
0.5	Gullies healed with vegetation indicating shallow flows
0.3 - 0.5	Channels intermittently gullied
0 - 0.4	Shallow, vegetated, ungullied or braided channels with evidence of deposition such as active alluvial fans or sediment deposits on bottomlands where flows spread naturally or are used for irrigation.

discharge onto fans at their mouths. Much of the flow is absorbed by the rocky fans, thus causing deposition of most of the sediment (point B in figure 2). These tributaries are assigned a relative sediment-delivery factor of 0.3. These results indicate a lower percentage of the area graded to the main channel than reported by Hadley (1961) for seven tributaries to Lance Creek in the upper Cheyenne River basin of Wyoming. However, Hadley's study was concerned with drainage area and this example involves measurements of percentage of gullied channels. Hadley found that 59 percent of the Lance Creek drainage was graded to the main channels and 41 percent was graded to flood plains or terraces. His results are analogous to the alluvial fan sediment-trap category of the present paper.

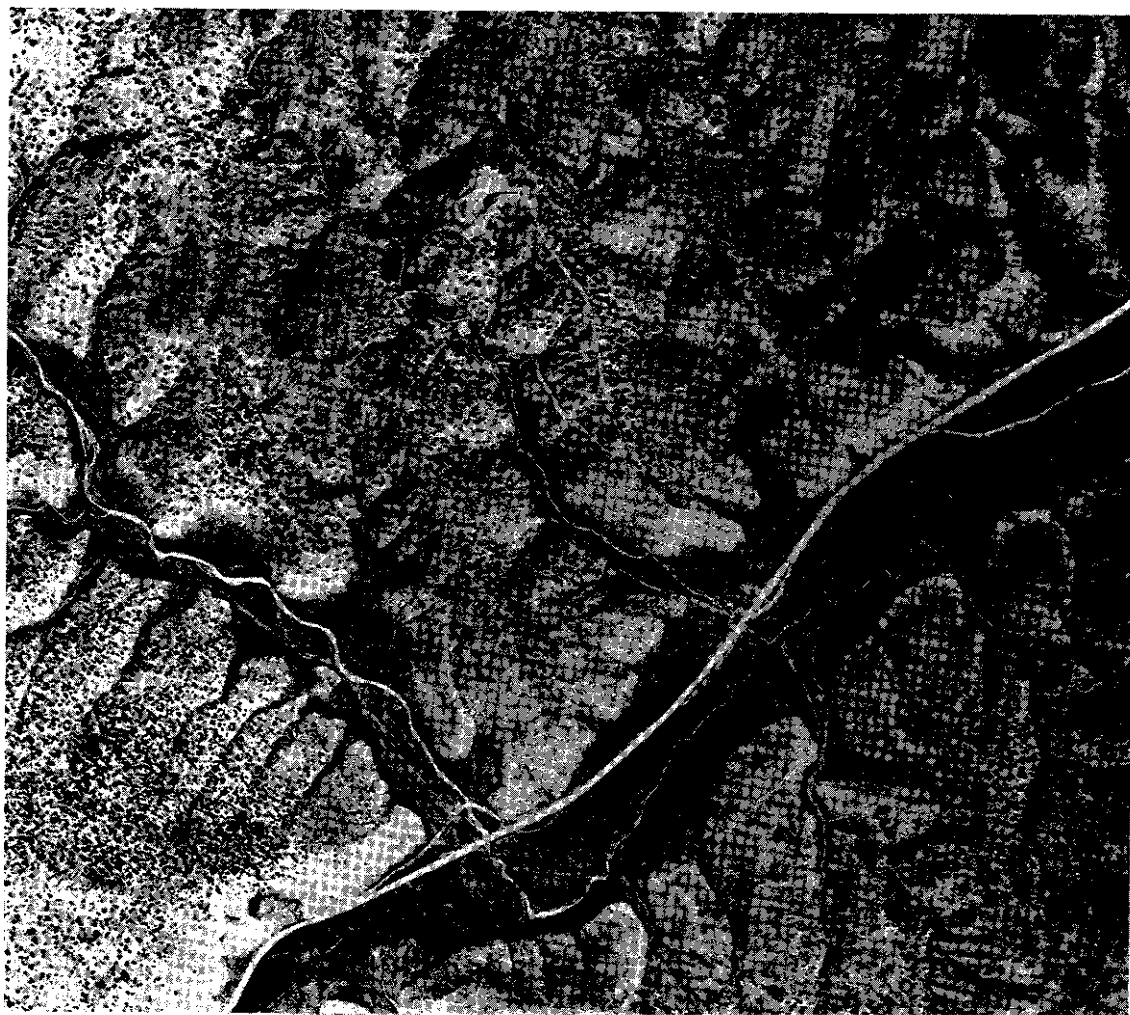


Figure 2.--Aerial photograph showing channel morphology and depositional features in the lower part of Ryan Gulch Basin. The center point of the photograph is at 39°54'56" North Latitude and 108°19' West Longitude.

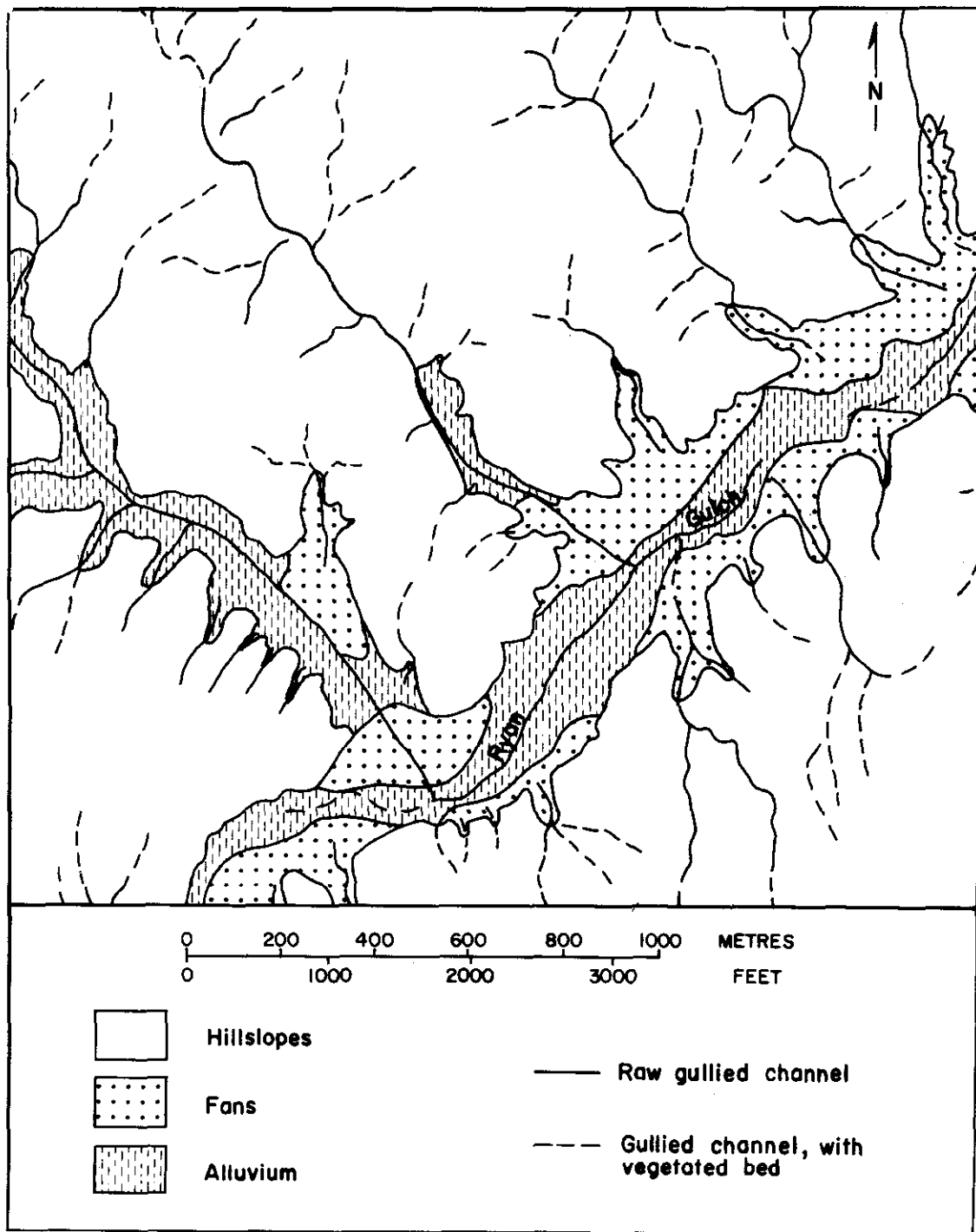


Figure 3.--Map showing channel morphology and landforms in the lower part of the Ryan Gulch basin. Map is the same scale and covers the same area as the photograph on opposite page.

Main valley channels--The total valley length in the Ryan Gulch basin is about 69.2 km (43 mi) including its mostly parallel tributaries which converge in the main valley about 12.9 km (8 mi) downstream from the upper divide to form a fifth-order channel. This total length is composed of 20 percent raw gullies, 63 percent gullies with vegetated beds and 17 percent poorly defined channels and braided rills as illustrated at points, C, D, and E, respectively, in figure 2. Sediment-delivery factors would be 0.75, 0.5, and 0.2 for points C, D, and E, respectively.

Infiltration of water into the sandy alluvium in the main valley is the chief factor that severely restricts sediment transport within and from the main Ryan Gulch valley. Flows are dissipated, therefore sediment is deposited at points such as C, D, and E (figure 2). Probably the only time that sediment is transported through untrenched reaches such as E is during wet years when the alluvium becomes saturated and during runoff events of large magnitude.

Frickel (1975) estimated the area-weighted mean sediment yield in the source areas of Ryan Gulch basin to be $285 \text{ m}^3/\text{km}^2$ (0.6 acre-ft per mi^2). Using a scheme similar to that shown in table 1 a mean basin sediment-delivery factor (conveyance) of 0.3 resulted from the length weighting of the various sediment-delivery factors assigned to individual reaches of channel. The resulting sediment yield from Ryan Gulch was $95.2 \text{ m}^3/\text{km}^2$ (0.2 acre-ft per mi^2). This means that only one-third of the amount of sediment yielded from areas of 0.5 to about 5.2 km^2 (2 mi^2) is transported to the mouth of Ryan Gulch. This is about the same percentage of sediment transported through the system as reported by Emmett (1974).

SUMMARY

The cycle of erosion in semiarid and arid drainage system is generally distinguished from that in more humid environments by the lack of accordance of many stream junctions and the characteristic diminution of streamflow due to absorption in dry, sandy channels. This loss of flow results in an increase in sediment concentration in a downstream direction and eventual deposition at intermediate sites in the system. These factors make the routing of sediment through the system a complex problem because many tributaries are responding independently to individual storm events. The foregoing analysis of sediment-transport processes is admittedly qualitative but a more quantitative model would require data on the processes and rates of transport from hillslopes to stream channels and the residence times of sediment at intermediate points.

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EROSION AND SEDIMENT FROM FOREST LAND USES,
MANAGEMENT PRACTICES AND DISTURBANCES IN THE
SOUTHEASTERN UNITED STATES

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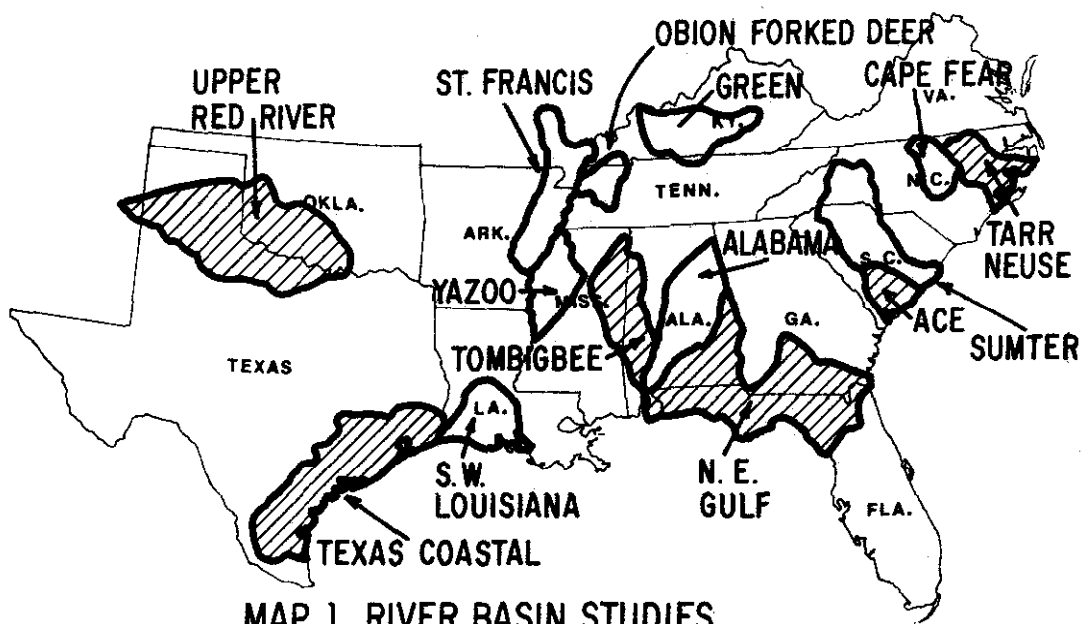
ABSTRACT

The data and information presented defines the nature, extent and magnitude of erosion and sediment sources from forested in several river basins in the Southeastern United States. Data shows that not all sediment from forest land is related to silviculture, but in some areas past abusive agriculture and present woodland overgrazing are the most important sources of sediment. It shows that forest practices acts, which contain blanket regulations, are likely to be inappropriate for some areas, insufficient for others or sometimes unnecessary. Control of forest sediment needs to be prescriptive and site specific in nature to meet not only water quality, but other resource needs.

INTRODUCTION

With passage of the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500), forest land managers need to know the nature, extent and magnitude of pollution from individual forest land uses and disturbances. With such information, they can adjust forest practices to accommodate water quality goals.

What do we know about sediment yield from forest land in the Southeastern United States? During the past seven years, erosion and sediment have been evaluated in 14 river basin studies (Map 1). Here, nearly 5000 field plots have been sampled to determine the nature, extent and magnitude of erosion and sediment problems associated with various forest land uses and forestry practices. This data has been analyzed by using the First Approximation of Suspended Sediment (FASS) procedure (Dissmeyer, 1973), which approximates the suspended sediment contribution of individual forest land uses or disturbances by associating back to the land units their proportional share of measured sediment output.



MAP 1 RIVER BASIN STUDIES

□ Sediment analysis completed ▨ Field data collected only

TABLE 1 Relative Contribution of Forest Land to Total Sediment Yield			
River Basin	% of Total Sediment	% of Basin In Forest	Sediment Yield Ratio
Alabama	24	68	.35
Cape Fear	6	68	.09
Green	2	34	.06
Obion-Forked Deer	8	24	.33
Santee	10	63	.16
St. Francis	3	18	.17
SW Louisiana	1	39	.03

PERSPECTIVE

One of the first questions to be answered is the matter of perspective: what percent of the total sediment yield comes from forest land as compared to nonforested lands? In seven basin studies where the analysis are complete, forests occupy from 18 to 68 percent of the area (TABLE 1), while the percent of total sediment yield produced by forest land ranges from 1 to 24 percent. This does not include stream channel erosion. Perspective can best be gained by computing the ratio of percent sediment production to percent of forest, which ranges from 0.03 to 0.35. The smaller the ratio, the smaller the relative contribution of forest land to sediment production. A ratio of 1.00 would mean that the forest was yielding sediment at the same rate as nonforested lands.

The two highest ratios occur in the Alabama and Obion-Forked Deer River Basins, where intensive mechanical site preparation and woodland overgrazing with high erosion rates are the causes, respectively. More discussion on individual sources of sediment will come later.

NATURE AND EXTENT OF FORESTRY PRACTICES AND LAND USES

When looking for sources of sediment in forest land, one must realize that the vast majority of the forest is undisturbed and not yielding more than natural levels of sediment from watershed slopes. The term undisturbed as used here does not mean virgin conditions, because most forest land has been disturbed sometime in the past. The term is used to describe the area that has not been disturbed in the past two to five years and the area is experiencing only natural erosion rates. For the nine basins for which area data has been developed, the area of forest in the undisturbed condition ranges from 69 to 94 percent (TABLE 2).

The percent of area logged each year varies due to the type of timber, the products grown and rotation. The area experiencing erosion and yielding sediment is a function of area cut and time required to heal disturbances. In the Southeast, the area experiencing erosion from logging ranges from 4.1 to 12.0 percent (TABLE 2).

The area experiencing erosion from skid trails, landings and spur roads was considered as a separate category from the logging area, because different control strategies are needed. Also, these areas tend to have somewhat longer recovery periods than areas where the trees are felled and removed. The area in spur roads, landings and skid trails ranges from 0.1 to 5.1 percent of the forest area.

TABLE 2. Percent of Forest Land Experiencing Erosion From Various Causes By River Basin						
River Basin	Undisturbed	Logging	Skid Trails Spur Roads and Landings	Fire	Grazing	Mechanical Site Preparation
Alabama	86	4.8	1.8	2.5	3.4	1.6
Cape Fear	93	4.1	1.0	1.6	Trace	0.5
Green	78	7.5	3.1	1.6	10.0	0.0
Obion-Forked Deer	81	9.0	5.1	0.5	9.4	0.0
Santee	94	4.5	0.1	0.7	Trace	0.5
St. Francis	78	12.0	1.1	0.7	8.0	0.0
SW Louisiana	69	6.1	0.5	10.5	13.4	Trace
Tar - Neuse	89	4.5	0.4	0.3	1.1	4.0
Yazoo	72	12.0	0.4	3.5	12.1	0.0

TABLE 3. Percent of Logged Area in Skid Trails and Spur Roads by Land Resource Area			
Land Resource Area	Percent of Logged Area in:		Total Area-%
	Skid Trails	Spur Roads	
Texas Claypan Area (87)	1.5	-	1.5
Central Miss. Valley Wooded Slopes (115)	1.3	7.0	8.3
Ozark Highland (116)	1.8	3.5	5.3
Ky. & Ind. Sandstone & Shale Hills & Valleys (120)	3.9	12.7	16.6
Highland Rim & Pennyroyal (122)	8.1	17.1	25.2
Southern Appalachian Ridges and Valleys (128)	8.3	1.2	9.5
Sand Mountain (129)	4.1	2.2	6.3
Blue Ridge (130)	3.0	2.2	5.2
Southern Miss. Valley Alluvium (131)	0.0	9.4	9.4
Southern Coastal Plain (133)	3.3	3.3	6.6
Southern Miss. Valley Silty Upland (134)	Trace	4.2	4.2
Ala. & Miss. Blackland Prairies(135)	6.1	7.3	13.4
Southern Piedmont (136)	4.3	1.9	6.2
Carolina & Ga. Sand Hills (137)	2.5	1.5	4.0
Atlanta Coast Flatwoods (153)	1.7	2.3	4.0

It should be noted here that not all spur roads found were exclusively used for logging. A portion of these roads are used for farm management, recreation, fire control, etc.

The percentages in skid trails and spur roads vary widely, because of differences in terrain among land resource areas (LRA), types of products being harvested and harvesting systems. The area in skid trails and spur roads, expressed as a percent of the logged area, by land resource area is presented in TABLE 3. In LRA's 131, 133, 134, 137 and 153, the primary product harvested is pulpwood in either thinnings or clearcuts. Here trees are felled and the pulpwood is usually stacked without skidding. Then trucks drive across the land to pick up the piles of pulpwood. Therefore, the area of skid trails is small. Also, because the trucks drive across the land, few spur roads are needed. Exceptions are where whole tree chippers are used and where sawlogs are harvested, which require skidding. However, such areas commonly are mechanically site prepared for planting, and skid trails and roads are obliterated.

In hilly and mountainous LRA's such as 120, 122, and 128, where hardwoods are harvested for sawlogs, roads are built to gain temporary access to timber, and logs are skidded to landings. Here, skid trails and spur roads can occupy between 9.5 and 25.2 percent of the logged area.

Fire includes both wildfire and prescribed burns. The area experiencing erosion from fire ranges from 0.3 to 10.5 percent (TABLE 2). When forests are managed for pine, fire is an important tool in controlling hardwoods. Also, fire is used to improve quail habitat.

Mechanical site preparation is used to prepare a site for planting pine. After a stand is harvested, the residual noncommercial pine and scrubby hardwoods are felled using heavy equipment. A variety of treatments are used including the following: chop; chop and burn; chop, burn and bed or disc; KG-blade, windrow and burn; KG-blade, windrow, burn and bed or disc; and bulldoze, windrow and burn. This is not an all inclusive list, but it does show the intensity of some treatments. The area in each basin experiencing erosion from mechanical site preparation ranges from zero to 4.0 percent.

Finally, the area experiencing woodland grazing ranges from essentially none to 13.4 percent of the forest land. Grazing is a viable and proper forestland use in some pine forests, but causes problems in hardwood forests. It is important to note that not all forest disturbances are exclusively related to silviculture.

RECOVERY TRENDS

An important concern in evaluating sediment from forest land uses and practices is how fast the affected areas heal. Disturbances from a few days to several years old were field sampled and the recovery trends

TABLE 4. Average Cover Factor; Recovery Trends in Cover Factors, and Representative Erosion rates for Various Forest Land Uses and Conditions by Land Resource Areas in Southeastern United States

(1) Land Resource Area	(2) Land Use or Condition	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		Average Cover Factor by Year During Recovery Period	Second Year	Third Year	Fourth Year	Fifth Year	C-factor for Period	Number of Plots	Representative Erosion Rate T/A/Y	Est. Sediment Productive 1/ T/A/Y
Central Rolling Red Plains (78)	Undisturbed	.002						40	.12	.00
	Grazed	.010						116	.58	.04
	Central Rolling Red Prairies (80)	.006						14	.05	.00
	Grazed	.008						46	.06	Trace
	Cross Timbers (84)	.004						52	.11	Trace
	Grazed	.005						64	.13	.00
	Grand Prairie (85)	.007						28	.51	.11
	Grazed	.007						41	.51	.11
	Texas Blackland Prairie (86)	.017						13	.33	Trace
	Grazed	.070						44	1.37	Trace
Texas Claypan Area (87)	Undisturbed	.027						32	.38	.14
	Grazed	.143						37	2.15	Trace
	Central Miss. Valley Wooded Slopes (115)	.004						22	.10	Trace
	Grazed	.008						8	2.54	.25
	Undisturbed	.006						78	.62	.02
	Grazed	.329						8	34.08	13.50
	Logged	.075	.032	.010				36	7.77	.39
	Spur Roads	.590	.158	.023				19	15.14	3.03
	Skid Trails	.610	.020	.033				8	17.09	.51
	Undisturbed	.004						106	.33	Trace
Kentucky and Indiana Sandstone and Shale Hills and Valleys (120)	Grazed	.119						14	9.68	.00
	Logged	.037						8	3.04	.30
	Highland Rim and Pennyroyal (122)	.012						8	.98	.00
	Undisturbed	.004	.005					143	.51	Trace
	Grazed	.203						35	25.77	10.31
	Logged	.014	.015	.013				24	1.78	Trace
	Spur Road	.525	.060	.300		.800		13	52.94	26.47
	Undisturbed	.003						25	1.29	.00
	Burned	.006	.005					13	2.15	.00
	Logged	.051	.029	.009				35	12.87	.39
Sand Mountain (129)	Undisturbed	.002						25	.91	Trace
	Logged	.006						15	23.54	2.82
	Blue Ridge (130)	.002						8	.77	.64
	Undisturbed	.033						32	12.76	.00
	Logged	.058	.007					7	105.20	12.08
	Skid Trails	.950	.346	.133				77	3.14	.09
	Undisturbed	.012						19	47.29	18.28
	Grazed	.181						9	3.40	.10
	Logged	.013	.012			.016		4	59.85	.00
	Spur Road	.453	.015					722	.53	.00
Southern Coastal Plain (133)	Undisturbed	.009						57	3.40	.71
	Burned	.058						240	4.17	2.23
	Grazed	.071	.096	.021	.010			19	3.52	.32
	Logged	.690	.950	.450				19	19.70	3.08
	Landings	.712	.635	.251	.005			45	20.21	6.27
	Spur Roads	.433	.567	.333	.003			43	14.23	4.41
	Skid Trails	.430	.272	.005				26	13.84	.78
	Chopping	.990	.700	.276	.133			12	30.80	12.50
	EG Blading	.790	.867	.216	.004			30	27.51	8.68
	Bulldozed	.750	.583	.333	.020			9	22.29	10.03
Southern Miss. Valley Alluvium (131)	Undisturbed	.800	.660	.137	.020			11	23.70	8.40
	Logged & Bedded	.767						6		
	EG Chopped, Burn	.190						3		
	Logged & Burned	.305	.482	.050	.010			21	12.44	.62
	Undisturbed	.005						480	.85	.12
	Burned	.060						12	10.18	.43
	Grazed	.145	.004					95	24.60	9.75
	Logged	.021	.008	.010	.005			90	2.04	.11
	Skid Trails	.567	.010					7	14.00	4.20
	Undisturbed	.012						95	.71	.00
Alabama & Miss (135) Blackland Prairies	Burned	.020						10	1.18	.01
	Grazed	.106						37	6.23	2.87
	Logged	.060	.129	.004				27	3.52	.35
	Spur Roads	.478	.700	.200				5	9.96	.10
	Undisturbed	.006						369	.55	.01
	Burned	.122	.007	.011	.007			13	11.19	1.40
	Grazed	.042	.074	.011				120	3.85	.76
	Logged	.475	.532	.750	.002			14	33.34	8.34
	Spur Roads	.840	.700	.271	.007			28	48.94	15.92
	Skid Trails	.845	.547	.401	.020			33	41.56	12.47
Carolina & Georgia Sand Hills (137)	EG Bladed	.750	.430	.125	.010			8	30.18	7.44
	Disced	.003						121	.07	Trace
	Undisturbed	.013	.010	.008				14	.22	.01
	Burned	.008	.023	.014	.013	.005		57	.29	.01
	Logged	.003						26	.02	.00
	Undisturbed	.157	.077					13	1.26	.11
	Logged	.892	.500	.990				9	10.34	1.44
	Spur Roads	.016						329	.13	.00
	Undisturbed	.010						4	.08	.00
	Grazed	.089	.066	.227	.010			72	.74	.00
Atlantic Coast Flatwoods (153)	Logged	.553	.900	.290		1.000		10	11.92	1.31
	Spur Roads	.227	.124	.090	.052	.016		18	.39	.00
	Skid Trails	.380	.202					6	2.43	.00
	Chopped	.450	.004					3	2.09	.00
	EG & Chopped	.993	.269	.050	.005			19	2.75	.27
	EG & Bedded									

1/ This is an estimate of all sediment that reaches the stream. Most sediment measurements are suspended sediment which would include only the fine particles (silt, clay, and fine sand) and would therefore, be somewhat lower than shown.

in cover factors (C-factor) were analyzed. Recovery trends are summarized by IRA and depicted for various forestry practices in TABLE 4. The recovery periods vary from 2 to 5 years.

In Column 8, the average cover-factor for the recovery period is presented. Note that undisturbed and grazed conditions are assumed to be static conditions and thus no recovery trend or period are defined.

A special problem in recovery trends is found for spur roads. Here, no trend can be defined because these roads are often not allowed to heal. They are used by the farmer for managing his farm; by hunters, jeepsters, and cyclists, and by forest managers and fire control personnel.

The number of plots taken in each condition is entered in Column 9 to indicate the relative reliability of the data. Some situations have strong data bases, and others are weak and shall be strengthened by future sampling.

REPRESENTATIVE EROSION RATES AND ESTIMATED SEDIMENT PRODUCTION RATES

Where sufficient data has been collected, representative erosion and estimated sediment production rates were computed (TABLE 4). From the data bank, the predominate soil was selected from each land resource area. For each soil grouping in the data bank, with its basic erosion rate (K); the average rainfall factor (R), slope (S) and slope length (L) were computed. Using these average values plus the average cover factor for the recovery period, a representative sheet erosion rate was computed using the modified Musgrave soil loss equation.

$$E = KCR \left(\frac{S}{10} \right)^{1.35} \left(\frac{L}{72.6} \right)^{.35}$$

(SCS, 1968) and is entered in Column 10. This rate approximates the middle ground for erosion from a forestry practice in a land resource area.

When the practices were field sampled, the observers estimated what proportion of the erosion reached the nearest stream (sediment delivery ratio) using techniques described by Dissmeyer (1973). For each practice and land resource area, a recovery trend in estimated sediment delivery was computed by slope class. An average sediment delivery ratio was computed for the recovery period and multiplied times the representative erosion rate to produce the estimated sediment production rate in Column 11.

RELATIVE CONTRIBUTION OF FOREST PRACTICES

The relative contribution of each forest management practice to sediment yield in eight completed studies is shown in TABLE 5, along with the

TABLE 5. Weighted Erosion Rates and Relative Contribution of Forest Practices to Forest Sediment Yield									
River Basin	Weighted Average Er. Rate T/A/Y	Forest Sediment P.P.M.	Percent of Forest Sediment by Source						
			Un- disturbed	Logged	Skid Trails	Spur Roads	Fire	Graz- ing	Site Prep.
Alabama	3.6	84	Trace	5	22	2	1	2	68
Cape Fear	0.4		Trace	20	11	11	28		30
Green	1.7		2	4	30	24	1	39	
Obion-Forked Deer	3.0		3	3	1	1	Trace	92	
Santee	0.7	34	Trace	1	7	2	10		80
St. Francis	1.2	9	1	14	10	27	1	47	
SW Louisiana	0.5		0 ¹ / ₂	2	38	Trace	1	Trace	
Yazoo	1.0		0 ² / ₃			37		21	

1/ Flood plain scour was responsible for 59 percent of sediment for forested area.

2/ 42% of the sediment is from erosion on old abandoned farm land being invaded by forest, but not yet stabilized by forest.

weighted average erosion rate for forest land in each basin. In three basins, average suspended sediment data was available and the portion contributed by forest land management has been approximated in parts per million using the FASS procedure.

The FASS procedure also identified what percent of the sediment yielded by forest land comes from each forestry practice or land use (TABLE 5). The results presented here clearly demonstrates that major causes of sediment vary from river basin to river basin. In some cases mechanical site preparation is the most important; in others, woodland overgrazing; and others spur roads and skid trails.

Also in the Southeast, not all sediment from forest land is from silviculture practices. In some areas, woodland overgrazing is clearly the major source of sediment. In other areas, former agriculture wore out and gullied the land. These lands were abandoned and forests either invaded or over planted. These lands are still eroding and the sediment is not due to present forest management, but past agricultural abuse.

Finally, this data clearly shows that forest practices acts, which contain blanket regulations, are likely to be inappropriate in some areas, insufficient in others or sometimes unnecessary. Control of sediment must be prescriptive and site specific in nature to meet not only water quality, but other resource needs. In some cases, more attention should be given nonsilvicultural land uses than to forestry.

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SEDIMENT PROBLEMS AND PLANNING IN THE SAN FRANCISCO BAY REGION,
CALIFORNIA

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ABSTRACT

A procedure has been developed to define the relations among terrain properties, human activities, and erosional and depositional processes and problems. The procedure involves four basic steps: (1) Identifying the critical physical elements that control erosion of the land, the transport of eroded materials, and the deposition of transported material; (2) analyzing the land surface using high-resolution aerial imagery; (3) mapping the erosional and depositional features and provinces; and (4) developing a planning matrix that relates land use to human activity. The procedure has been applied in the San Francisco Bay region, California, and the Willamette River basin, Oregon.

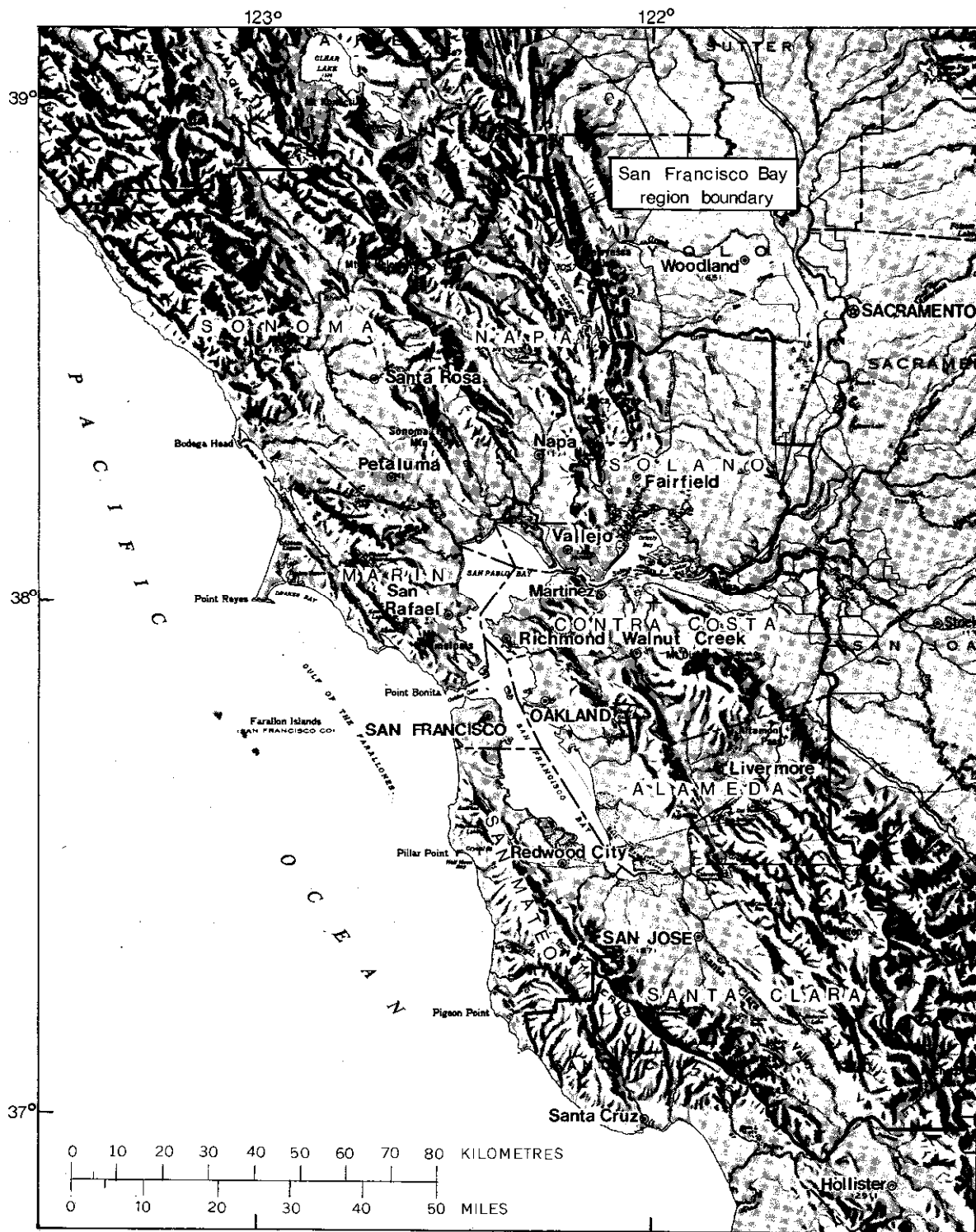
The San Francisco Bay region, vastly altered by human activities during a 200-year period, experiences serious and pervasive sediment-related problems. Today no significant unaltered part of the region exists from which quantitative conclusions regarding "natural" versus "human-affected" sedimentation conditions can be reasonably drawn. A review of present-day problems reveals that their early solution is not in the realm of the resource scientist but first must await action by the political community.

INTRODUCTION

The San Francisco Bay region (fig. 1) is defined by the political boundaries of nine counties surrounding the San Francisco Bay estuary. The bay region thus includes about 19,000 km² (7,400 mi²) of land and water that has long been regarded as one of the most desirable environments for human existence in the world. The many favorable and remarkably diverse aspects of the land, air, water, fauna, and flora that compose the region offer great advantage for human living conditions. As a result the bay region has attracted rapid population growth and presently is the place of residence for nearly 5 million people.

The people largely inhabit the lowlands peripheral to the central and southern parts of the estuary. There, urban-suburban expansion has created a continuous built-up belt extending from San Francisco southeasterly to San Jose, and thence northwesterly to Richmond. Additional expansion persists in the valley southeast of San Jose and radiates from such urban cores as Livermore, Walnut Creek, Petaluma, Santa Rosa, Vallejo, Napa, and Fairfield. A cursory inspection of the relief shown in figure 1 will reveal that most of the urban centers are on flat to gently sloping terrain. Nevertheless, the pressures of urban-suburban expansion on the lowlands and valley floors have led to considerable development of foothill and mountainous areas peripheral to the flats. Thus, a rather definite pattern of further urban-suburban expansion is cast, and the use of steeply sloping land for building purposes has become a planning problem of major proportions. In particular, planners and developers need information on the stability of steep slopes. Furthermore, they need to know the probable travel routes of moving sediment, the probable areas of deposition, and the quantities of sediment that might be deposited. Such information, together with other environmental data, would be useful in delineating areas that are hazardous for building or that need protective structures.

The San Francisco Bay region is an exemplary site for the study of flatland and hillside building, their interrelations, and consequent problems. Notably, the bay region contains diverse landforms, a variety of microclimates, dense urban development, and a rapidly expanding population. The interactions among these elements provide several models of experience that can be applied in many other regions. Indeed, a cooperative study by the U.S. Geological Survey and the U.S. Department of Housing and Urban Development was designed to delineate and evaluate the natural physical features, resources, hazards, and processes of the bay region and to seek regional-analysis models that might apply elsewhere. The products of the study are aimed at providing the planning and decisionmaking community with natural science information in support of efforts to:



Base from U.S. Geological Survey
State of California base map,
1:1,000,000.

FIGURE 1.--Relief map of the San Francisco Bay region.

1. Minimize disruption of those aspects of the environment that make a community or region a desirable place to live;
2. Avoid unnecessary and uneconomic risks from geologic and hydrologic hazards;
3. Avoid detrimental interactions between natural processes and human activities; and
4. Use the natural resources--both renewable and nonrenewable--in a manner that is compatible with orderly development and that results in economic use and environmental protection.

One primary element of the study was a regional analysis of erosion, transportation, and deposition of sediment and interpretations of the analysis for regional planning and management uses. The remainder of this paper describes the evolution, results, and impact of the sediment studies and outlines a method for communicating sediment-related information effectively to planners and managers.

A REVIEW OF BASIC PROBLEMS

The initial finding on erosion, transportation, and deposition of sediment in the San Francisco Bay region can be simply stated: Sediment data were commonly lacking where needed and obscure in meaning (particularly to the planning community) where data did exist. Sediment data consisted primarily of concentrations and size analyses in concert with stream-discharge measurements and reservoir surveys. The data were commonly collected for special-purpose projects, and sampling sites were not necessarily selected with community or regional planning in mind. Thus, several major parts of the bay region were devoid of a conventional sediment data base. Because the establishment of a data base in those areas would in itself exhaust the time and funding allocated for the study, alternative methods for understanding the sediment situation became mandatory. A review of the problem suggested first that members of the planning community be asked what they know and want to know about sediment. The responses indicated that the following questions be answered in planning reports.

1. What is sediment?
2. From where does sediment come?
3. Where does sediment go?
4. What causes sediment to move?
5. What problems does sediment cause?
6. Where and how frequently do the problems occur?
7. How serious are the problems in terms of lives and dollars (damage, cleanup, and person-hours of time)?
8. How many of the problems occur naturally and how many are related to human activity?
9. How can the problems be alleviated?

The planners who were consulted also suggested that the information in planning reports be presented, inasmuch as possible, in nontechnical language and in a simple graphical, map, or photographic format.

A LANDFORM CONCEPT FOR PLANNING

The answers to many of the questions posed in the previous section are not commonly found by the analysis of the sediment discharge of streams. The answers may be more readily found by analyzing landforms. A landform is defined as:

"Any physical, recognizable form or feature of the Earth's surface, having a characteristic shape, and produced by natural causes; it includes major forms such as a plain, plateau, or mountain, and minor forms such as a hill, valley, slope, esker, or dune. Taken together, the landforms make up the surface configuration of the Earth" (Gary and others, 1972, p. 395).

Sediment is derived from erosional landforms. Sediment is deposited to build depositional landforms. Geologic information about the landforms suggests the type of sediment available and its rate of erosion or accumulation. A cursory inspection of a landform may suggest whether it is susceptible to, or has been deposited by the action of flowing water, flowing ice, organisms, wind, gravity, water waves, or human activities. An inspection of an undisturbed part of a landform may reveal the naturally occurring erosional or depositional features. A look at the human activities on a particular landform suggests the problems that sediment may cause, why the problems occur, and what to do about them.

A landform analysis technique, therefore, was applied in the San Francisco Bay region (Brown and Jackson, 1973, 1974) in a preliminary form. The technique was subsequently revised and applied in studies of the Willamette River basin, Oregon (Rickert and Hines, 1975; Hines and others, 1975). The technique involves four basic steps.

1. The critical physical elements that control erosion of the land, the transport of eroded materials, and the deposition of transported material are identified and collated for a given region. The critical physical elements may be found among the seven factors affecting worldwide sediment movement. First, there is *gravity* that translates into forces of motion of soil and rock debris and also controls the energy potential of certain climatic forces to act on the Earth's surface. Second, there is *geology*, including the attributes of rocks from which sediment is derived. Third, there are *soils*, or the loose surface materials of the Earth consisting of disintegrated rock mixed with organic matter. Fourth, there is *climate*, or the aspects of the atmosphere that interact with rock and soil surfaces. Fifth, there is *vegetation* that commonly is an interface between soils and climate and is dependent upon both for its sustenance. Sixth, there is *topography*, or the aspects of slope that affect the energy of climatic forces and the influence of gravity. Seventh, there is *human activity* that variably affects the other six factors. For any region on Earth of any size, assumptions and criteria can be developed for defining distinctive units of terrain herein called erosional and depositional provinces and defined as follows:

Erosional province--An association of erosional landforms.

Depositional province--An association of depositional landforms.

2. An analysis of the present-day land surface is made using aerial imagery. Preferably, the imagery should be color infrared imagery obtained from satellite or high-altitude aircraft flights. The color infrared imagery affords high resolution over a broad area and dramatically accentuates erosional and depositional features. The erosional and depositional features are observed and analyzed as to their probable causes and effects using the aerial imagery and appropriate ground checking.
3. Erosional and depositional features and provinces are mapped on a suitable base (Vickers and Brown, 1975). The base should be selected only after consultation with prospective users and should be easily readable. Fully or semicontrolled photomosaic bases are excellent for depicting landforms and human activities, although other standard and less expensive maps would also suffice. The completed base allows the presentation of an up-to-date, synoptic view of erosional and depositional provinces, features, problems, and related surface conditions, both natural and human-affected.

4. An erosional or depositional problem matrix is developed. The matrix shows selected human activities along the horizontal axis and erosional or depositional features along the vertical axis. A matrix may be developed for each erosional or depositional province. The body of the matrix may be filled with numerical or symbolic information that indicates the relative impact of an activity association with an erosional or depositional feature. Thus, the matrix allows the planner to estimate the relative severity of erosional or depositional problems (or potential) in different provinces as a function of human activity. Alternatively, a matrix may be produced that lists provinces as columns and human activities as rows. From information compiled on the map base, the provinces are ranked numerically in order of their potential to erode or to accommodate deposition. The human activities are ranked numerically in their order of land-surface disruption as interpreted from aerial imagery. The magnitude of the numerical rank from each column and row would indicate the relative seriousness of erosional or depositional problems likely to develop under the various combinations of provinces and human activities. As an aid to problem solving, the matrix boxes (fig. 2) may be split to offer space for a number, letter, or symbol that would guide the user to a solution reference. The reference may be a report, or it may be one of a set of guidelines in an appendix to the matrix.

The four-step procedure would provide information that is useful to land, air, and water-resource planning. The principal attributes are: (1) Graphic depiction of the relations among terrain properties, human activities, and impacts on erosion, transportation, and deposition of sediment; (2) provision of information to resource planners and scientists in a ready-to-use format; and (3) amenability to regular updating to provide information under rapidly changing conditions. The techniques are flexible and may be readily modified for studies of any area. At a minimum, the techniques would demonstrate vividly the data needs for analyzing an area in terms of land, air, and water quality. At a maximum, the techniques would provide a predictive guide to land-use planning and regulation in terms of the overall physical quality of an area.

PROVINCES AND SEDIMENT PROBLEMS IN THE SAN FRANCISCO BAY REGION

The techniques described in the previous section, applied and revised during studies of the San Francisco Bay region, provided much useful information. In this section, some of the information is summarized. However, the reader is encouraged to consult the reference list for specific items that could not be expanded upon in this short paper.

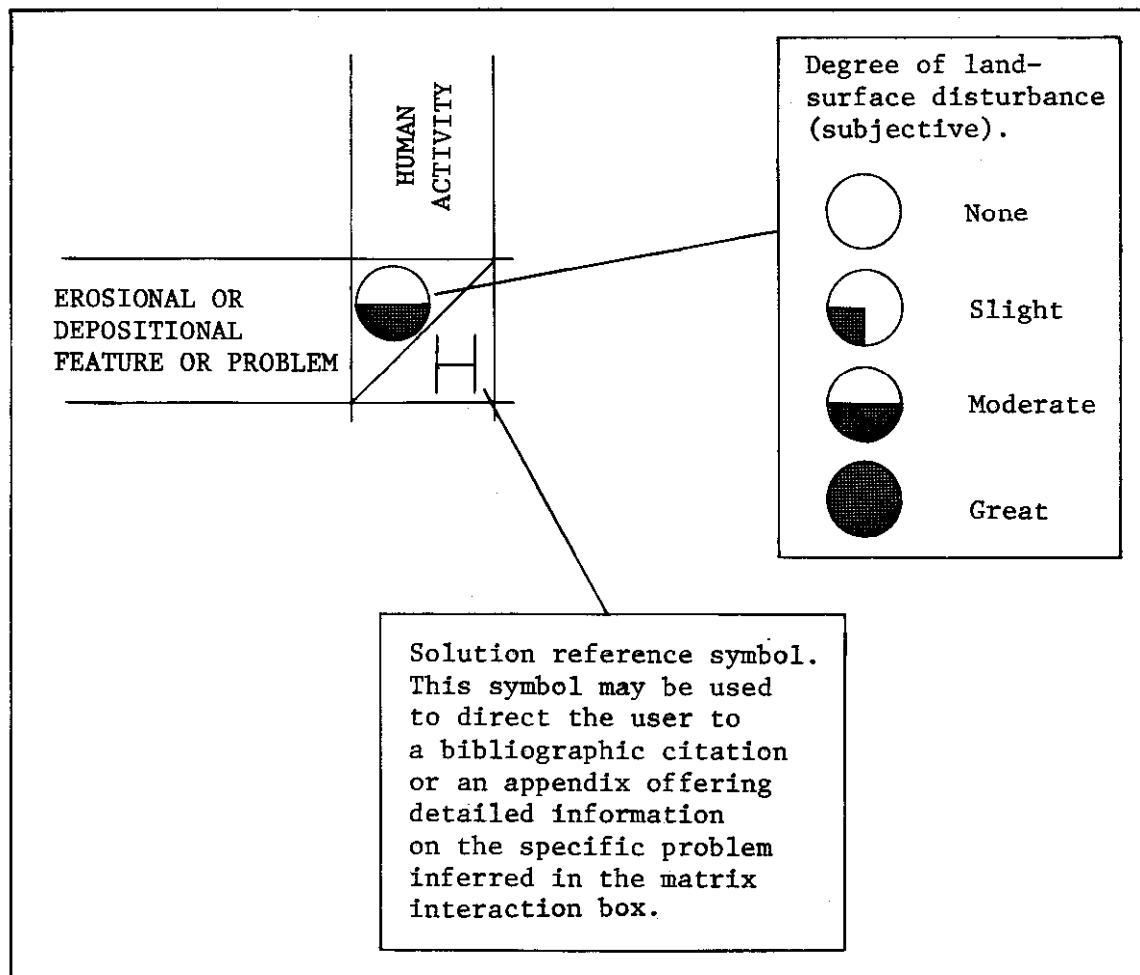


FIGURE 2.--Schematic of a matrix interaction box showing a simple, symbolic-alphabetical notation code. Many variations on this theme are possible, but the matrix body should be uncluttered and easily readable.

A brief overview of the San Francisco Bay region suggests the categorization shown in table 1. In practice, province boundaries were well-defined by geomorphic criteria, and 18 provinces were mapped for a single subregion of the bay region. Thus, table 1 serves only as a guide for discussion purposes and does not reflect the detail expressed in the referenced reports.

The bay region is currently beset with sediment-related problems largely due to human activities. Accelerated gullying may have begun in the late 1700's when the foothills south of San Francisco were subjected to logging, grazing, and land conversion by the colonizing Spaniards. Major deposition in the estuary during the late 1800's was ascribed to hydraulic mining for gold in the Sierra Nevada to the east (Gilbert, 1917, p. 8). Logging, roadbuilding, land conversion, and artificial filling of the bay combined during the past century to imbalance further any natural sedimentation processes in the region. Currently, no river flows unaltered into the San Francisco Bay estuary, and no major tract of land in the nine-county region retains all of its natural geomorphic facets. Certainly, sediment yield has been decreased in many areas due to the protective aspects of pavement or careful agricultural practices. However, the onset of paving, clearing, and tillage is commonly accompanied by temporary but major increases in sediment yield (Knott, 1973; Wolman, 1967). In any event, no significant unaltered part of the region exists today from which quantitative conclusions regarding "natural" versus "human-affected" sedimentation conditions can be reasonably drawn.

Nevertheless, several useful statements regarding sediment problems and processes in the bay region can be made, and these will aptly serve to conclude this paper.

1. Present-day erosion is most severe and widespread in the mountainous uplands of northwestern Sonoma County. Accelerated erosion began there during the late 1800's and persists today because of intensive roadbuilding, logging, grazing, and land conversion (Poli and Roberts, 1958; U.S. Department of Agriculture, 1966). Sediment yield data and definitive studies of coastal streams in the area are lacking.

TABLE 1.--*Summary of geomorphic conditions in the San Francisco Bay region and related sediment problems*
 [Location of place names shown in figure 1]

Landform associations	Example location(s)	Typical problems	Sediment yield (erosional) or accumulation rate (depositional)	Remarks
<u>Dominantly erosional province types</u>				
Mountainous uplands (near-coastal)	Western Marin, Sonoma, and San Mateo Counties.	Landsliding; road cut and fill failures; streambed aggradation; gullyng.	High to extreme: long-term suspended-sediment yields in excess of 2,500 (t/km ²)/yr in Sonoma County.	Human activities have caused disturbance of unstable terrain in high rainfall areas producing numerous fresh erosional features.
Mountainous uplands (interior)	Eastern Sonoma County; Napa County; eastern Santa Clara County.	Landsliding; gullies; wind erosion of exposed surfaces.	Low to moderate: long-term suspended-sediment yields less than 150 (t/km ²)/yr in eastern Santa Clara County.	Although terrain is highly unstable, erosional activity is not sustained because of dry climate. Also, land-surface disturbance by human activities is minor compared to other areas.
Foothills (coastal and peripheral to San Francisco Bay)	Marin-Sonoma County border; western San Mateo County; bayward exposures of all counties excepting San Francisco.	Gullyng; road cut and fill failures; reservoir sedimentation; rilling on construction sites.	Moderate to very high: long-term suspended-sediment yields about 1,000 (t/km ²)/hr in western Contra Costa and Alameda Counties.	Rapid suburban expansion in foothill areas commonly generates numerous erosional problems. Short-term yields may be extreme.

TABLE 1.--*Summary of geomorphic conditions in the San Francisco Bay region
and related sediment problems--Continued*

Landform associations	Example location(s)	Typical problems	Sediment yield (erosional) or accumulation rate (depositional)	Remarks
<u>Dominantly erosional province types--Continued</u>				
Foothills (interior)	Northwestern and southeastern Solano County; eastern Contra Costa and Alameda Counties.	Minor gullying and landsliding; wind erosion of exposed surfaces.	Sediment yield unmeasured, but lack of erosional activity suggests very low yields.	Dry climate and soil conservation practices inhibit erosion.
<u>Dominantly depositional province types</u>				
Alluvial valleys	Central Sonoma County; central Napa County; central Alameda County; central Santa Clara County.	Streambed aggradation; streambank failure; overbank deposits; flooding.	Accumulation rates in river channels variable and largely unmeasured.	Gravel mining, dredging, and stream channelization are common. Erosion of channel banks is a major problem.
Marshlands and mudflats	All counties; margins of the San Francisco Bay estuary.	Shoaling; concentration of sediment-borne pollutants; excessive turbidity; damage to waterfront equipment; reduced estuarine circulation.	Deposition and disposal of dredged waste have added 135 km ² of land to the bay since the mid-1800's.	Marshland areas were reduced from 810 to 324 km ² , or to 40 percent of their size in mid-1800's, dominantly by human activity.

TABLE 1.--*Summary of geomorphic conditions in the San Francisco Bay region
and related sediment problems--Continued*

Landform associations	Example location(s)	Typical problems	Sediment yield (erosional) or accumulation rate (depositional)	Remarks
<u>Mixed erosional and depositional province types</u>				
Coastal (Pacific coastline)	Western borders of Sonoma, Marin, San Francisco, and San Mateo Counties.	Coastal retreat; landsliding; road and housing site failures.	Sediment movement in the coastal zone is largely unmeasured.	Coastal retreat rates commonly exceed 0.5 m/yr on coastal terraces of San Mateo County.
Upland valleys and ridgetops (isolated in larger units)	All counties excepting San Francisco.	Minor gullying and landsliding; minor streambed aggradation and streambank failures in valleys.	Sediment yield largely unmeasured, but probably much lower than that of surrounding terrain.	Ridgetop erosion is largely related to roadbuilding along ridges.

2. Excessive, short-term sediment yields and numerous sediment-related problems have been noted for foothill areas subjected to rapid suburbanization (Knott, 1973). Building in foothill areas probably will continue to produce the bulk of new, short-lived, small-scale sediment problems. The aggregate cost of the solutions to such problems probably will be large and not easily estimated. Further, most of these problems could be avoided by careful construction practices.
3. The massive problems of dredging in the navigation channels of the San Francisco Bay estuary probably cannot be resolved to the extent where dredging would no longer be necessary. The mass of sediment in circulation in the estuary, placed during the past century within the confinement of dikes and landfill, probably will not reach an equilibrium pattern consistent with navigation needs for the next several decades. The problems of dredging and dredge-waste disposal have accrued during the past century and may be ascribed to a variety of sources.
4. Conflicts caused by aggregate mining in river channels and in areas of suburban expansion will persist as building and agricultural space on alluvial flats decreases. No definitive studies of aggregate-mining effects on river channel morphology have been made in the bay region.
5. Shoreline erosion and sediment transport in the coastal zone will become highly important factors in the resolution of plans for the Pacific shoreline of the bay region. Definitive studies of sediment transport in the coastal zone of the bay region are currently lacking.
6. Most sediment-related problems, although widespread and pervasive, can be located, predicted, interpreted, and solved. Solutions to many of these problems are documented, are readily available to the public, and in many instances, funding specifically marked for their application is available. Communication between the scientist, those who alter the land, and those who formulate and enforce soil conservation practices is needed to resolve or prevent these problems.

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SIMULATING EROSION DYNAMICS WITH A DETERMINISTIC DISTRIBUTED WATERSHED MODEL

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ABSTRACT

A simulation model is described which incorporates the differential equation for continuity of suspended sediment into a kinematic numerical model for hydraulic response of a watershed surface. The model is practical since it includes an advanced infiltration function and has the ability to accept complex rainfall patterns. Relatively complex watershed shapes may be simulated using a watershed composed of small branched channels fed by an arrangement of non-rectangular, converging planes with distorted slopes.

The realism of the model's ability to simulate sediment production is limited by the necessity to specify rather empirical functions for soil detachment rates from rainfall impact and from flowing water. Either tractive force or stream power function may be chosen as a model for sediment-carrying capacity.

Several examples are shown to demonstrate the capabilities of such a dynamic and distributed simulation of watershed sediment production, including effects on erosion of rainfall patterns, slope convergence, and comparative sediment-production rainfall, overland flow, and channel flow.

INTRODUCTION

Since the pioneering work of Wooding (1965) and Woolhiser (1967), many watershed models have employed the kinematic wave equations to represent the hydraulics of watershed surface flow. There have also been many field and laboratory demonstrations of the validity of the kinematic assumption.

Flow of water on the surface of a watershed is only one part of a complex process, dependent on many variables and processes, but on which other processes, like erosion, are in turn dependent. No theoretical model can accurately simulate all the processes, as well as the complex spatial variation and inhomogeneities. Nevertheless, evolution of simpler, engineering models depends on assessing the relative merit of alternative approximations to nature; to evaluate simplifying assumptions, complex but more complete models must be constructed.

A rather complex but efficient kinematic watershed model being developed for this purpose is employed here, since it provides the basis of a model for water-borne pollution transport. Space limitations do not allow either a complete model description or a comprehensive demonstration of its capabilities, but several examples of results are presented.

The Basic Hydraulic Model

Wooding (1965) employed a simple rectangle, with flow parallel to one dimension, to represent the watershed surface as part of an elementary watershed. Since then, a cascade of planes of various sizes and slopes (Brakensiek, 1967; Kibler, 1970) or a converging section of a cone (Woolhiser, 1971) have been used for geometric representation of complex surfaces. Mathematical treatment can be made more general by including variable slope, length, and convergence, in a single kinematic equation. This usually eliminates the need to model a watershed with an awkward assembly of rectangular planes. In the definition sketch of Figure 1, convergence is expressed by the variation in width, w , of a hypothetical uniformly widening plane, so that

$$w = w_0 + b(L-x) = w_m - bx \quad (1)$$

where L is maximum distance from stream perpendicular to the contours, x is measured from upstream point L , and $w_m = w_0 + bL$ is width of hypothetical plane at its top. This does not limit application to watersheds which widen uniformly, since this relation can be considered to describe only convergence rate. Convergence is 0 for $b = 0$, and flow lines diverge for negative b .

The continuity equation then becomes

$$w \frac{\partial h}{\partial t} + \frac{\partial (uhw)}{\partial x} = qw \quad (2)$$

or

$$\begin{aligned} \frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} &= q - \frac{uh}{w} \frac{\partial w}{\partial x} \\ &= q + \frac{buh}{w_m - bx} \end{aligned} \quad (3)$$

where h is point surface water depth

t is time

x is distance from upstream edge of plane

u is point velocity

and q is input rate of rainfall excess.

Smoothly varying slope $S = S(x)$ may be simulated in evaluating the term $\partial (uh)$, since $u = u(h, s)$. Moreover, the kinematic rating equation

$$u = C_f S^m h^n, \quad (4)$$

where C_f is a friction coefficient, may incorporate both laminar and turbulent flow, since C , m , and n are functions of flow regime, transition of which occurs at a specified critical Reynolds number (Woolhiser, 1970).

With these modifications, numerical simulation of a linearly distorted plane proceeds similarly to that discussed by Kibler (1970), using a Lax-Wendroff, second-order, explicit scheme. For efficiency, a Crank-Nickolsen type implicit method is used in stream channels.

Channel hydraulics are analagous to that of the planes, except that at channel depths a transitional friction relation is unnecessary, and areas are used in place of depth, h , in Equations 2 and 4. In Equation 2, $q(x,t)$ for a channel is the sum of the plane output from each side of the channel (cfs/ft) multiplied by the cosine of the respective mean angle of interception of the channel, θ (Figure 1).

For a plane with variable flow-path lengths ($L = L(x)$), solution of depth at each t along the longest path provides information for estimating channel discharges for shorter path lengths. This efficient approximation is inaccurate, however, if $S = S(x)$ is not true for x in all flow paths.

Infiltration Submodel

Critical to accurate subhumid watershed simulation is the computation of water actually forming the source of overland flow. The model employed here is basically that reported by Smith (1973) with improvements by Parlange (1975). This model allows accurate prediction of ponding time and explicit interaction of surface hydraulic conditions with infiltration calculations at all points along the surface. This contrasts with methods calculating excess from rainfall, routed over an impervious surface; infiltration continues as long as water remains on the surface, independent of rainfall after runoff begins.

Erosion-Sedimentation Submodel

Bennett (1974) presented a comprehensive discussion of sediment yield modeling. A good model of sediment production from a watershed depends heavily on the accuracy of the hydrologic model for water flow. Following Bennett (1974), but ignoring the dispersion term, the continuity equation for sediment on the watershed surface may be written

$$\frac{\partial (hc)}{\partial t} + \frac{\partial (huc)}{\partial x} + (1-d) \frac{\partial z}{\partial t} = 0 \quad (5)$$

where c is concentration of sediment (or other water-borne pollutant), z is surface soil depth, and d is surface soil porosity. The term including z is the sediment-production term, which includes erosion from raindrop impact, as well as erosion and deposition by moving water. Dispersion is not considered in this kinematic simulation.

Empirical functions describing erosion processes are well discussed in the literature. Wischmeier (1958) introduced a factor EI to represent erosive energy of rainfall and further incorporated the concept into a soil loss equation (Wischmeier, 1960) for small plots based on overall storm depth. Meyer (1969) extended this analysis to an empirical, steady-state model for erosion and sediment yield from plane, one-dimensional surfaces, but did not compare results with field data. Foster (1972) included transient conditions under uniform rainfall by including a linear carrying capacity-detachment relation, where erosion rate is essentially a linear function of transport capacity deficit.

Numerically, Equation 5 is solved implicitly with a time-weighted, four-point method at each time step, after Equations 2 and 4 are solved for the arrays of h and u . Empirical functions for rate of erosion by rainfall and transport capacity of flowing water are supplied as interchangeable subroutines. A linear erosion-deposition model for rate, similar to that of Foster, is used so that over an interval (Δt), average erosion or deposition rate ($\overline{ef}$) may be derived as

$$\overline{ef} = G(c - c_{mx}) e^{-G\Delta t} \quad (6)$$

where c_{mx} is transport capacity as concentration at any point x , c is current sediment concentration, and G is a rate-controlling parameter.

Local transport capacity, c_{mx} , may be computed from several possible empirical relationships involving dependence on velocity, slope, and depth of flow. A tractive force relation was used by Meyer (1969):

$$c_{mx} = \frac{C_s u^{2.5}}{h}, \quad (7)$$

where C_s is a soil-dependent parameter. Several other relationships resulted from experimental work by Kilinc (1973). A critical tractive force or "stream power concept from Yang (1972) is employed here;

$$c_{mx} = \frac{C_o [u(\tau_o - \tau_c)]^{1.58}}{\gamma u h} \quad (8)$$

where τ_o is boundary shear force, τ_c is critical boundary shear (tractive force), γ is unit weight of water, and C_o is a coefficient. For channel sediment transport capacity, the unit stream power concept from Yang (1972) is employed here:

$$\log c_{mx} = A + B \log (uS - \overline{uS_o}) \quad (9)$$

where A , B and $\overline{uS_o}$ are parameters. Tractive force relations are as easily applied.

Rain splash erosion may be related to the second power of rainfall rate, as in Meyer (1969). This reportedly produces results similar to the experimentally based Soil Loss Equation now in wide use. Choice of empirical erosion and transport relations is critical, although the primary purpose here is the development of a framework within which alternative erosion and transport models may be compared.

Sample Model Applications

If the relative complexity of a watershed is measured by the density of the channel network developed therein, then simulation of more complex watersheds is largely a problem in computer software and storage capacity. Elementary watershed units, like the pattern in Figure 1, will suffice here to demonstrate essential ability of the watershed erosion model and to indicate some erosion phenomena that presently are not quantified.

The sediment and water discharge simulated for one sample rainfall and elementary watershed are shown in Figure 2. For this example, the sediment discharge generally conforms to the water discharge hydrograph. There is a small amount of hysteresis as the model structure dictates, since aside from rain splash erosion, the sediment transport capacity would lead the actual concentration during rising discharge as Equation 6 implies.

The particular relations used yield approximately 0.25 Mt (0.28T) total sediment production for the 6.4 mm (.25 in) rainfall event on this 1.13-ha (2.9 a) watershed. It should not be inferred that this pattern of sediment production is necessarily typical. The actual pattern of erosion should be controlled by the relative erosive importance of rainfall and surface water flow.

The pattern of sediment discharge entering the watershed channels is of particular interest with respect to erosion processes on the watershed surface. Figure 3 shows hysteretic sediment discharge rating for a simple plane surface. Two sediment capacity laws are compared for this purpose, one from Bagnold using a stream power concept (Kilinc, 1973), labeled S_1 , [equation (8)] and another employing a tractive force method from Meyer (1969), labeled S_2 [equation (8)]. Parameters were chosen to match c_{mx} at the flow peak. What appear to be discontinuities on the rising half of each curve occur at time of transition from laminar to turbulent flow at the lower end of the plane. Also shown on this graph is the steady-state relation of discharge to carrying capacity of flow, c_{mx} , for each assumed relation. The sediment discharge leads the c_{mx} relation only at the earliest part of the hydrograph, resulting from rain splash erosion; otherwise the lag is as in a simple linear system.

Figure 4 is the time-dependent analogy of Figure 3, showing changes in sediment concentration of plane discharge, rather than sediment discharge. Here the effect of the transition in hydraulic roughness law seems more dramatic on the recession. The particular form of the relation of sediment concentration, c_{mx} , to u and h governs the reaction of the sediment concentration to this small perturbation in hydraulic response. Such a transition has been observed and is more than a theoretical-numerical phenomenon (Woolhiser 1971), although it is diffused, well masked, and not crucial in real watershed data. The simulated role of rain splash erosion can, in part, be observed by the result (shown in Figure 4), for which the splash erosion coefficient is increased by a factor of 10. Since these relations in this demonstration are arbitrary, the case is not excluded in which most of the sediment is produced early, as a result of rain erosion, and the erosion by overland-flowing water is minimal. Further, this model does not attempt to account for the possible case where rainfall before runoff loosens surface soil and produces material much more easily transported than that available at the surface during later flow. These effects conceivably could reverse the hysteresis associated with surface hydraulic erosion.

Figure 5 presents modeled results of the time evolution of cumulative watershed erosion in terms of small changes in soil depth. Figure 5a is the rainfall rate pattern on this hypothetical elementary watershed--two rectangular, sinusoidally-sloped, convergent planes feeding a central channel. Figure 5b shows net watershed depth changes

on each plane. The effects of the variable slope are evident: convergence of flow simply distorts the effect at the lower end; a nonconvergent plane would exhibit a longer length of late-storm deposition. For this sinusoidal slope, deposition at the lower end continues after erosion on the steep central area has virtually ceased, owing to deceleration of flow in this area.

Storm-based changes in the central channel, (Figure 5c), are somewhat different. The channel responds to the sediment introduced from the planes along its length, as well as to the channel sediment transport capacity dictated by the empirical function adopted (Yang, 1972). In this example, the channel tends to steepen (from an interesting combination of upstream deposition and downstream erosion), related mostly to the longitudinal velocity distribution. This pattern would be somewhat altered in field cases by downstream hydraulic control. It seems that by proper choice of (variable) channel slope, one could minimize event-related changes in channel profile. This suggests a relation between mean watershed erosion, geometry, and evolution of relatively stable upland channel slope profiles.

Summary

Limited space has prevented more than a summary presentation of the basic abilities of this watershed transport model. The general objective here has been the description of the model as a framework within which alternative erosion and transport models may be evaluated.

The structure of the watershed model allows complex watershed shapes to be more accurately modeled, and the erosion submodel is treated as a completely time-varying relation; previous models have either dealt with lumped events or assumed uniform rainfall rate.

Results presented here on hypothetical watersheds demonstrate sensitivities to relative erosivity of rainfall and flowing water, choice of erosion models, and accuracy of hydraulic simulation.

Such features as rill development, for example, could be incorporated by modifying the surface hydraulic equations to operate with hydraulic description of rills with a varying relation of mean depth and hydraulic radius or by treating flow dominated by rills in a partitioned manner as is done with overbank flood flow.

A more extensive study of model sensitivity, inclusion of other detail, and comparison of model with field data now being assembled are planned for a subsequent report.

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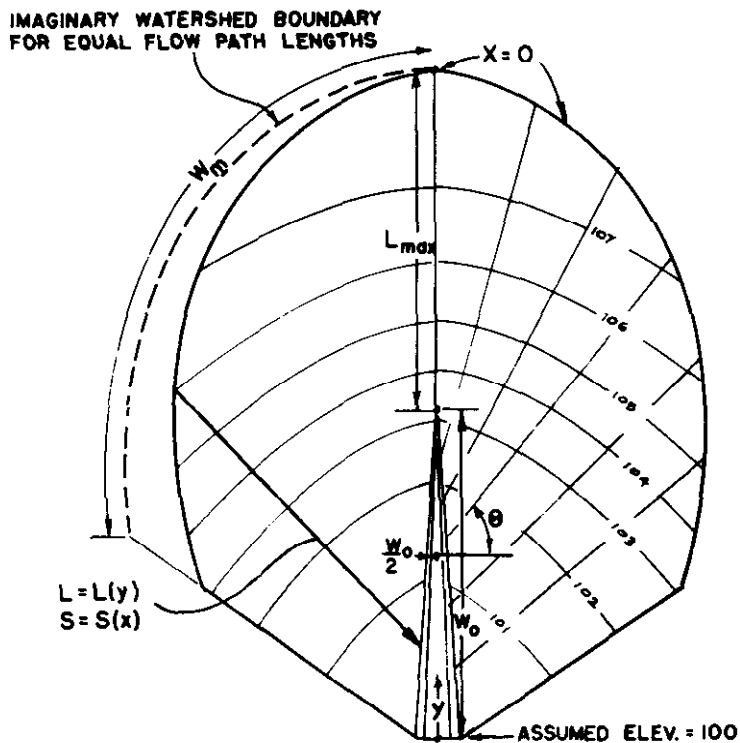


Figure 1. Definition Sketch for Example Watershed Geometry.

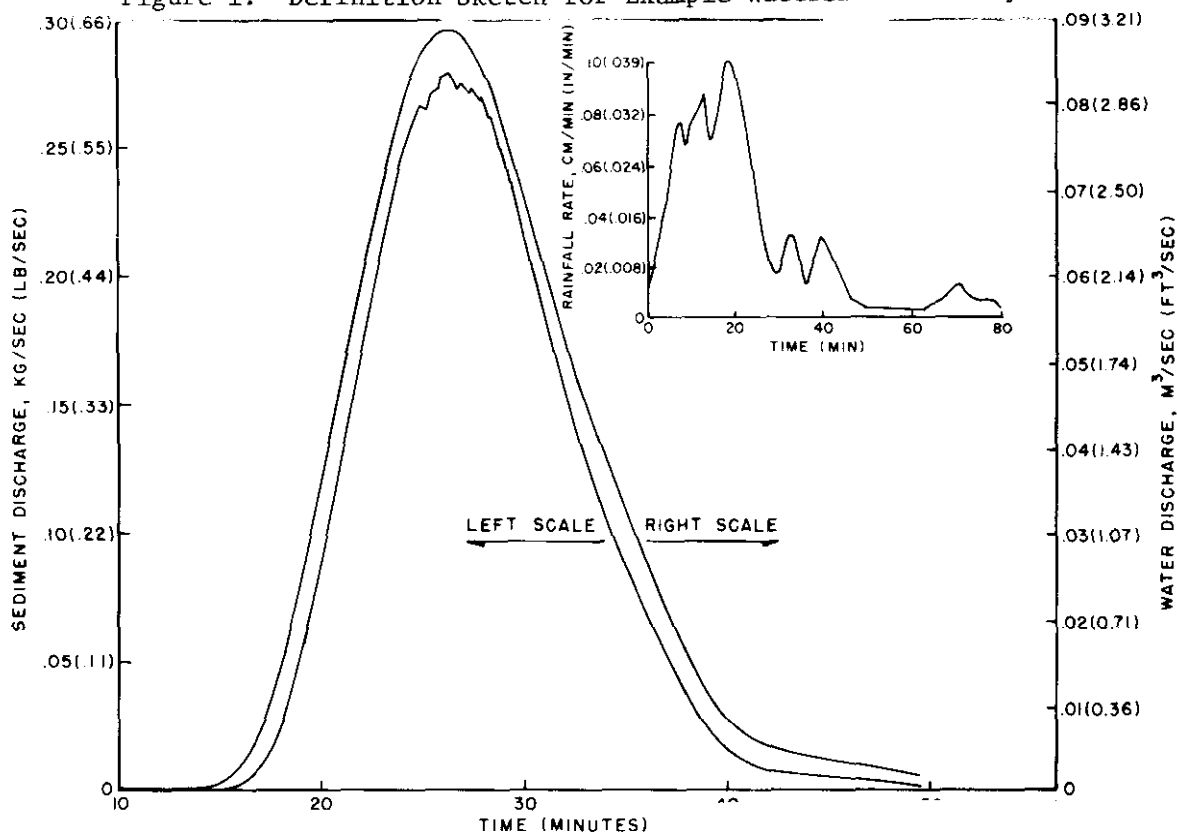


Figure 2. Sample Discharge-Time Graphs for Water and Sediment From a Small Single-Channel Watershed.

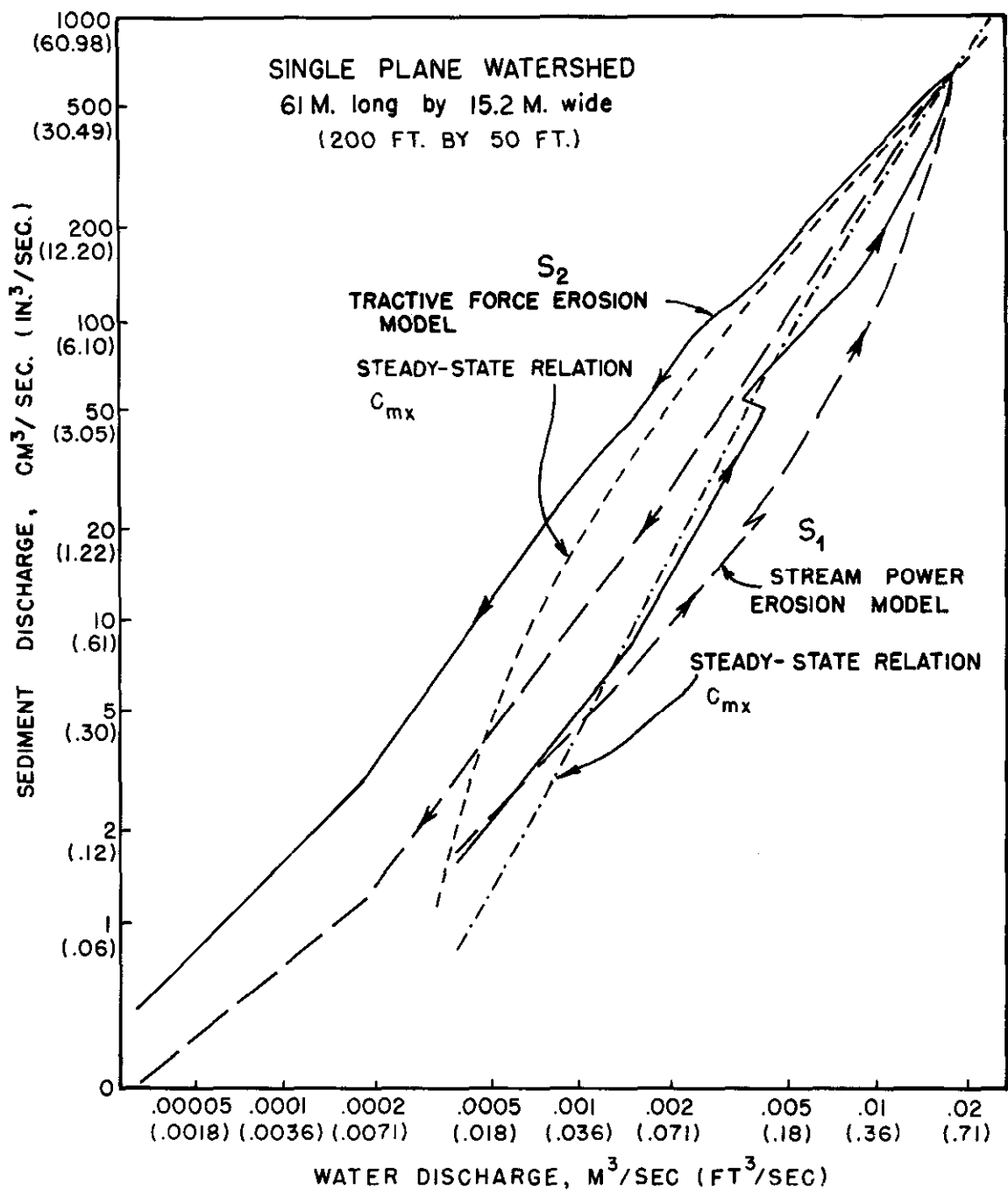


Figure 3. Hysteresis in Sediment Discharge Rating Relation for Inflow into Simple Watershed Channel.

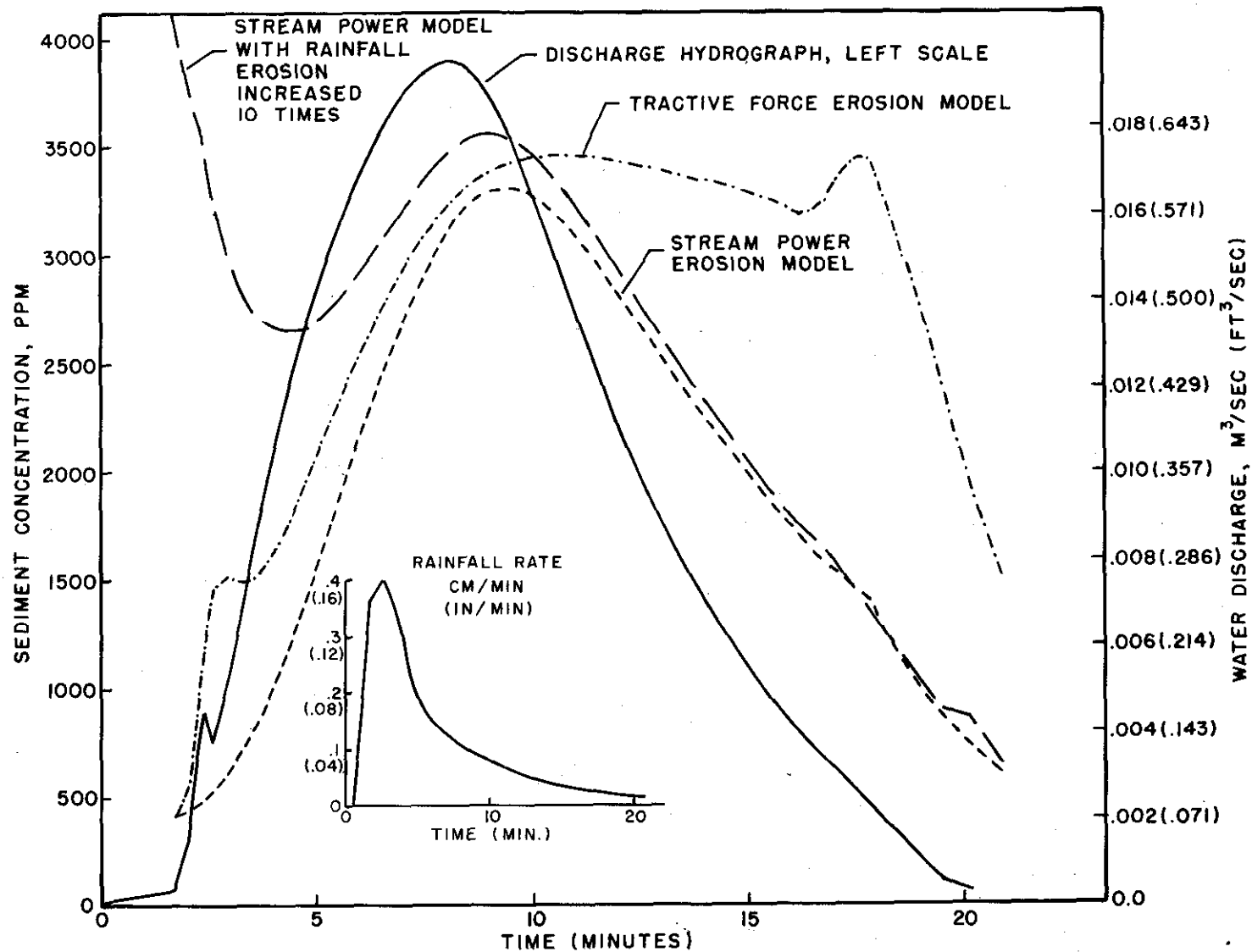


Figure 4. Time Pattern of Water and Sediment Discharge Simulated from Simple Plane Surface.

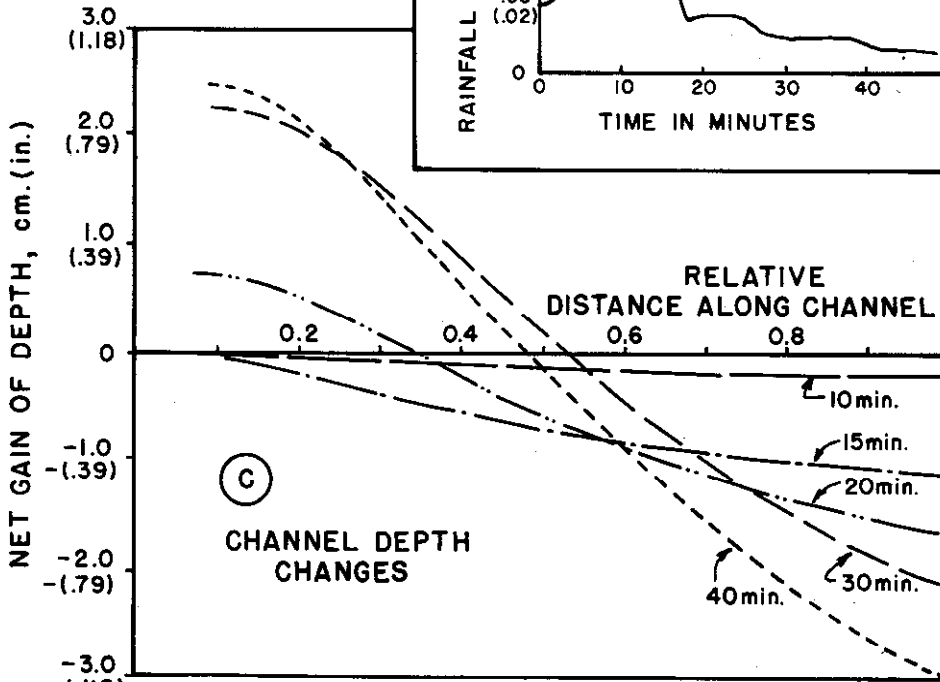
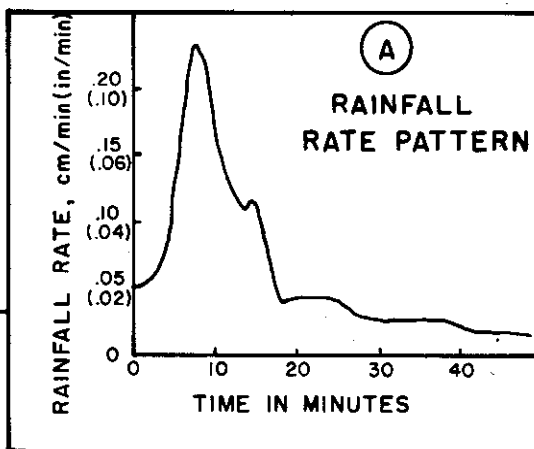
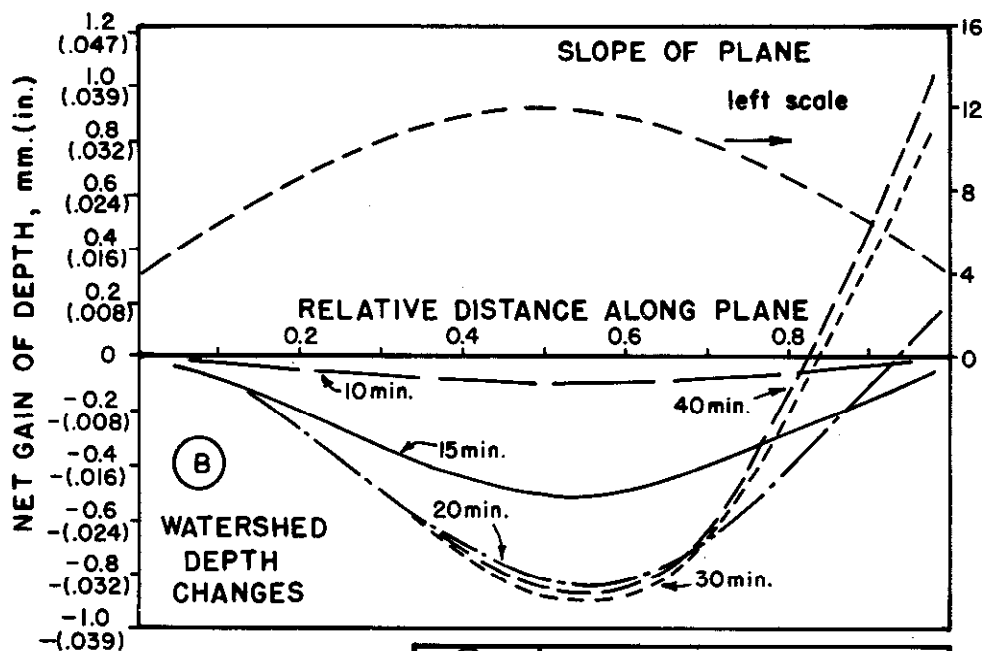


Figure 5. Time Evolution of Surface Depth Changes Simulated for Land and Channel Surfaces.

SEDIMENTATION OF A FLATLAND WATERSHED IN LOUISIANA

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ABSTRACT

Recent emphasis on the downstream effects of the Public Law 566 flatland watersheds has created an additional need to examine the various aspects of the sedimentary process in areas of low relief. Presently accepted evaluation procedures were developed in areas of greater relief and generally dealt with coarser soils. The data for evaluation described here is a joint effort between the Agricultural Research Service (ARS), the United States Geological Survey (USGS), and the Soil Conservation Service (SCS). Each group has unique expertise, and the coalition of this expertise is expected to furnish the maximum knowledge in minimum time at minimum expense. Basic sheet erosion has been determined by ARS using a "rainfall simulator." Sediment in transport is being measured by USGS using PS-69 samplers. Rates of sediment deposition are being measured by ARS using Cesium-137 concentrations as date markers. SCS is monitoring activities that affect the land, providing personnel in the immediate area, correlating activities dealing with the study, analyzing results of the various studies, and evaluating the elements of the sedimentary process.

INTRODUCTION

The area being studied is located in southern Louisiana where the greatest relief is the natural levees (maximum elevations between 20 and 25 feet) of Bayou Lafourche and the present Mississippi River (Figure 1). The natural levee of Bayou Lafourche reflects a period of time (from approximately 1100 AD to 1900 AD) when Bayou Lafourche served as a diversion of the Mississippi River. The similarity of age and deposition between the natural levee of the present Mississippi River and the natural levee of Bayou Lafourche provides a situation where the soils and slopes of the two different natural levees are similar. There is a definite break in the slopes where the natural levee intersects the backswamp deposits. The backswamp deposits gradually merge into Lake Verret. Average slopes on the natural levee are approximately 0.07 percent. The local slopes due to minor breaks are somewhat larger and are estimated to generally average about 0.2 percent. The soils on these levees are approximately 80 percent Commerce and 20 percent Convent. Land use is primarily

agriculture, sugarcane acreage accounting for more than 90 percent. The soils of the backswamp are in the Sharkey series. General slopes average approximately 0.04 percent, but locally they are estimated to average approximately 0.2 percent. Slope lengths between quarter drains average approximately 300 feet on both the Commerce and Sharkey soils. Sugarcane and some soybeans are grown on the Sharkey soils but the most of Sharkey soils are used for woodland production. Where the woodland is above 4 feet mean sea level, hardwoods are the dominating vegetation. Below 4 feet mean sea level, the woodland is predominately cypress-tupelo. The elevation of Lake Verret normally ranges between 1 and 3 feet above mean sea level.

The concept being used in this study is the multiple checking of each element of the sedimentary process by comparing and correlating data derived by different methods.

The rate of erosion has been computed by the Universal Soil-Loss Equation (USLE) (Wischmeier and Smith, 1965), the Musgrave Equation (Musgrave, 1947), and field checked by measurements from the "rainfall simulator" (Meyer and McCane, 1958). Measurements of material being removed from a 560-acre drainage area are being made on a storm basis with PS-69 automatic samplers (Water Resources Council, 1972) and the rainfall from each of the storms will be converted to the "EI" factor (Wischmeier and Smith, 1958) in the USLE. Crop stage will be noted for comparison. Data developed from these methods will be used to predict rates of erosion.

In addition to the continuous sampler being used to establish erosion rates, three other PS-69 sampling stations and a "grab sample" station have been installed. The sampling stations have been located to evaluate sediment delivery ratios, the effects of a sump area on sediment delivery ratios, the effects of channel deposition on sediment delivery ratios, and to act as a check on the station measuring erosion. This information will be related to a factor relating drainage area and channel density. It will also be related to storm runoff and the curve for estimating sediment delivery ratios in the Blackland Prairies Problem Area (Maner and Barnes, 1953). The rate of sediment deposition, as established by the Cesium-137 concentration study (Ritchie et al., in press), versus the determined erosion rate will also be used to establish a sediment delivery ratio.

The sediment accumulation rate at Lake Verret and the trap efficiency of the lake are being checked by measurements of the Cesium-137 concentrations in the bottom sediment. Sediment samples have been taken from the bottom of main bayous entering Lake Verret, Lake Palourde, and from downstream lakes connected to Lake Verret.

The sampling station being used to evaluate erosion (Station No. 4) monitors a drainage area of 560 acres. Ten of these acres are occupied by a sugar refinery. The remaining acreage is planted in sugarcane. The area has Commerce soils. Using the Musgrave Equation to compute erosion, the average erosion rate "E" is 0.79 tons per acre per year. This amount is based on a soil factor "F" of 104, a rainfall factor "R" of 1.75, an adjusted slope "S" of 0.01, and a cover factor "C" of 0.433.

$$E = FRSC$$

$$E = 104 \times 1.75 \times 0.01 \times 0.433$$

$$E = 0.79 \text{ tons per acre per year}$$

Using the USLE (A=RKLS_{CP}), average erosion (A) amounts to 4.55 tons per acre per year. The following values for the factors were used:

$$R, \text{ the rainfall factor,} = 350$$

$$K, \text{ the soil erodibility factor,} = 0.37$$

$$LS, \text{ the percent slope and slope length factor,} = 0.11$$

(based on M = 0.3)

$$C, \text{ the annual crop management factor,} = 0.32$$

$$P, \text{ the erosion-control practice factor,} = 1$$

$$A = 350 \times 0.37 \times 0.11 \times 0.32 \times 1 = 4.55 \text{ tons per acre per year}$$

Rainfall simulator tests were conducted on the Commerce soils of this drainage area. Tests were conducted under cover conditions of "flat-fallow," "bare-rows," "stubble," and "full-canopy." The annual "C" factor of 0.32 used in the above computation was derived from these tests. Erosion rates computed from the rainfall simulator data were considered to be very high and the data is being reexamined.

The PS-69 sampler monitoring the erosion from simulator-tested areas is still being rated. Extreme difficulties have been experienced in relating stream gage elevations to flow velocities. Differences in the stage of Lake Verret and the confluence of other channels which drain much larger areas below the station cause the difficulty. When this problem is solved, erosion of the controlled drainage area will be equated with the sediment yield to the station. Sediment will be computed on a storm basis; the "R" factor in the USLE will be computed from the rainfall gage records; and the frequency of the storms will be established. From this, an average annual erosion rate will be approximated and compared to the other rates that have been developed.

Difficulty has been experienced at all of the PS-69 sampling stations. The trouble has ranged from sediment collecting on the floats and prohibiting the activation of the sampler to having the same flow velocity at different stream gage elevations. The

mechanical difficulties have been readily overcome, but the flow ratings are still in the process of being evaluated. In addition to the normal stream gage installations at each of the four PS-69 sampling stations, Station 3 (located on Grand Bayou) has vanes installed to show the direction of flow. It has been observed that upstream flow occurs at all stations. This flow is being correlated with the flow direction as recorded by the vane at Grand Bayou. The present plans for rating the flow at the different stations include the correlation of the vane information and development of a flow gradient. In addition to this procedure, an experimental recording flow meter is to be installed by USGS.

Sediment discharge from several storms has been computed at PS-69 Stations 1 and 2. While this information will be modified as the flow rates are refined, the information is considered to have approximately 25 percent accuracy.

At Site No. 1, a total of 6,690 tons of sediment were calculated as being discharged as a result of a total of 6.48 inches of rain. The drainage area above Site No. 1 is 22.6 square miles.

Site No. 2 had a total of 19,163 tons of sediment calculated for 12.26 inches of rainfall. The drainage area for Site No. 2 is 37.2 square miles.

Bottom samples of the sediment in 27 different locations have been taken in Grand Bayou, Bayou Carne, Lake Verret, Grassy Lake, and Lake Palourde. These samples were analyzed qualitatively and quantitatively for Cesium-137. The peak concentrations were assumed to represent the peak cesium depositional years of 1962-64. The six locations sampled in Grand Bayou and Bayou Carne had sediment thickness above the maximum concentration, in centimeters, of 30-40; 30-40; 30-40; 10-20; 50-60; and 30-40, respectively. This would indicate approximately 4 cm/year (0.13 ft/year) of sediment being accumulated in these bayous. The 11 locations sampled in Lake Verret showed a wide variation in thickness of sediment to maximum concentrations (0 to 40 cm or 0-1.3 ft). Most of the sediment appears to be in deltas where major streams are entering the lake and no deposition is occurring near the center of the lake. Four locations were sampled in Grassy Lake. Three of the locations (the inlet from Lake Verret, the inlet from the east, and the center of the lake) showed little or no sediment. The fourth location, in the exit section, showed a peak concentration between 10 and 20 cm (0.3 and 0.6 ft). Nine locations were sampled in Lake Palourde. With the exception of the location near the mouth of Bayou Milhomme (Belle River), very little sediment was observed. It is thought that most of the sediment entering Lake Palourde has a source other than Lake Verret.

Additional locations will be sampled for Cesium-137 concentrations. Band 6 ERTS photographs show anomalous conditions in the areas of high deposition. These areas will be sampled and if the results indicate a correlation between sediment deposition and the photographs, the photographs will be used to determine the area of deposition. Samples will be taken in the swamp area north of Lake Verret along Grand Bayou and Bayou Carne. Channels between Lake Verret and Lake Palourde will be sampled.

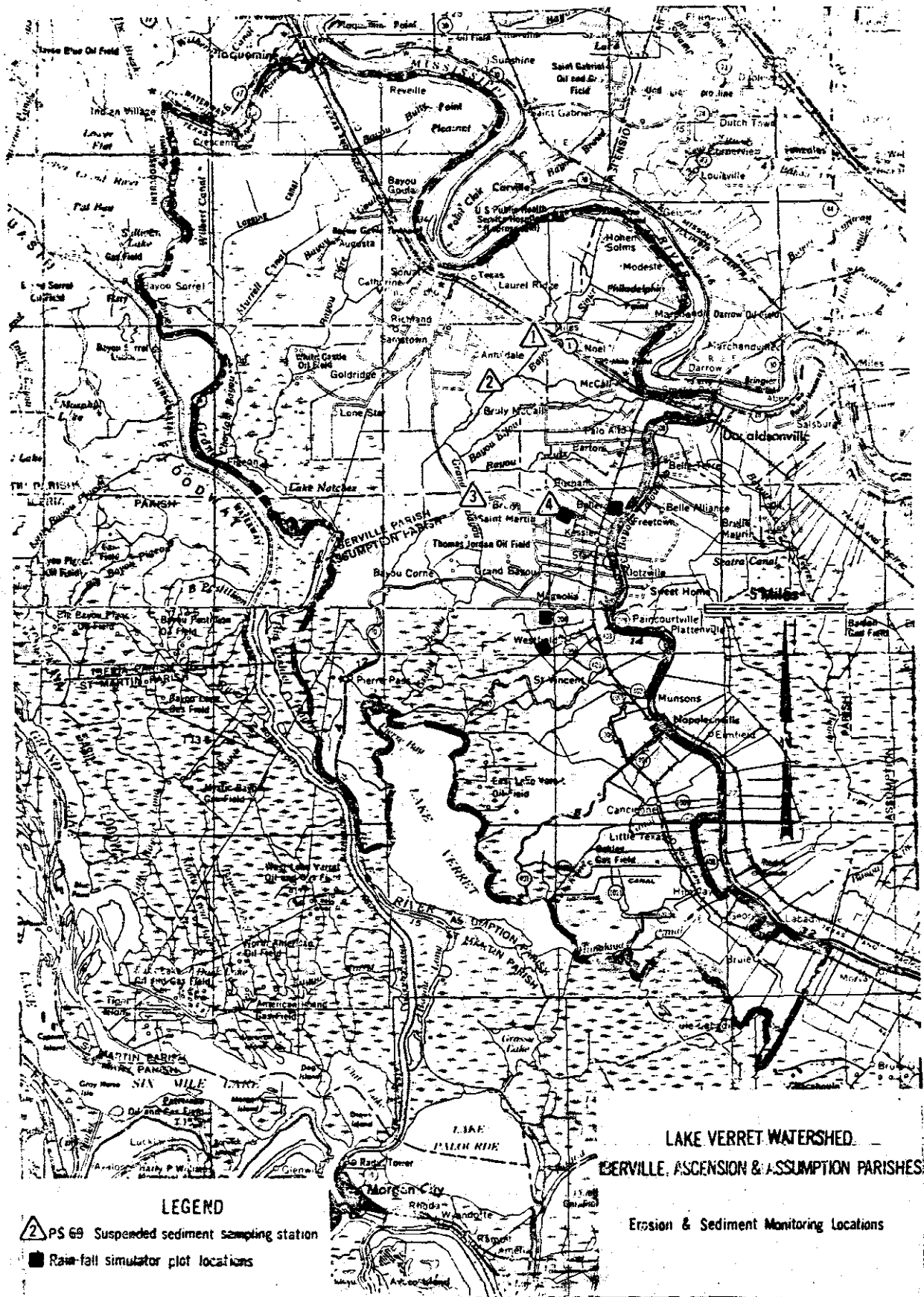
Although additional time is necessary to accomplish the goals of this study, preliminary results of the various tests are encouraging. The ability of Lake Verret to trap sediment, prior to its being deposited in Lake Palourde, has been established by the Cesium-137 study. The rainfall simulator tests established the erodible nature of the soils and have shown the necessity of additional erosion studies on soils with low slopes. The PS-69 samplers have established the presence of a high sediment yield, and the preliminary data seems to substantiate the high erosion rates found with the rainfall simulator.

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Wischmeier, Walter H., and D. D. Smith. Rainfall Energy and Its Relationship to Soil Loss, Transactions, American Geophysical Union, Vol. 39, No. 2, 285-291, 1958.

Figure 1



STORM-PERIOD VARIABLES AFFECTING SEDIMENT TRANSPORT FROM URBAN CONSTRUCTION AREAS

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ABSTRACT

Eight small drainage basins, ranging in size from 0.91 to 25.2 square kilometres (0.35 to 9.73 square miles), located in the suburbs of Washington, D.C., were studied between 1963 and 1974 to determine sediment transport characteristics of streams draining urban construction areas. Annual construction ranged from less than 1 percent of basin area to more than 15 percent. Five hundred and twenty-four storms were analyzed to determine the effects of 14 storm-period variables on sediment load. Factors found to be most significant were storm runoff and peak discharge. Rainfall intensity, runoff peakedness, percentage of basin under construction, and a time-trend factor were found to be less significant. Multiple correlation coefficients for best regression equations with four independent variables ranged from 0.85 to 0.96, and standard errors ranged from 0.300 to 0.221 log units. The equations reflect the significant impact of both construction activities and summer storms on the sediment discharge of urban streams.

INTRODUCTION

Suspended-sediment discharge of streams is highly variable, depending on runoff conditions, rainfall duration and intensity, and land use. The relative effects of some of these factors on individual storm-sediment loads have been analyzed for several large drainage basins in the Atlantic coast area (Guy, 1964). Basins ranging in size from 255 to 11,840 km² (square kilometres) or 98.4 to 4,571 mi² (square miles) were studied. Factors such as storm runoff, runoff peak ratio, and rainfall intensity explained much of the storm-to-storm variation of sediment discharge for these large basins. This paper presents the results of a similar investigation of small urban streams, and illustrates sediment-load response to various storm-related parameters in areas undergoing urban development.

The drainage basins studied are located in the headwaters of the Rock Creek and Anacostia River basins in Montgomery County, Md. (fig. 1) Physiographic and climatic conditions of the study area are generally representative of the Piedmont Plateau between central Virginia and northern New Jersey. The typical upland topography is gently rolling, and the stream valleys are steep and narrow. The predominant soils are silt loams and silty clay loams formed from a residuum of igneous and

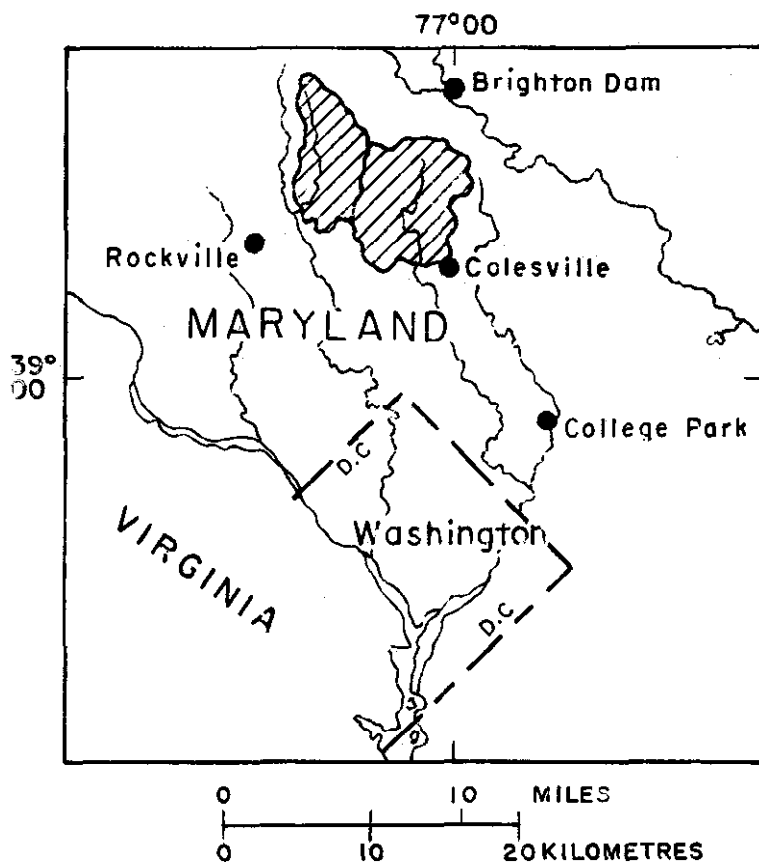


Figure 1.--Location of study area (shaded).

metamorphic rocks. These soils are highly susceptible to erosion when exposed by construction activities. Precipitation averages about 1,070 mm/yr (42 in/yr), and is evenly distributed throughout the year. Average monthly precipitation ranges from 71 mm (2.8 in) in February, to 124 mm (4.9 in) in August. Much of the summer precipitation comes in short, high-intensity rainfalls from convective storms, whereas winter precipitation comes mostly in low-intensity rainfall from frontal storms.

Streamflow, precipitation, suspended-sediment, and land-use data were obtained for eight drainage basins in the study area between 1963 and 1974. The basins ranged in size from 0.91 to 25.2 km² (0.35 to 9.73 mi²). Four of the basins remained mostly rural during the study period, while the remaining four basins underwent considerable development (table 1). Streamflow was monitored at each site with digital water-stage recorders having recording frequencies of 96 or 288 readings per day, depending on basin drainage area and land use. Recording rain gages in each basin were used to obtain rainfall intensity. A supplementary network of nonrecording rain gages was used to define the areal

TABLE 1.--INFORMATION ON BASINS USED IN REGRESSION ANALYSIS OF THE EFFECTS OF STORM-PERIOD VARIABLES

BASIN	DRAINAGE AREA KM ²	PERIOD OF RECORD	NUMBER OF		PERCENTAGE OF BASIN UNDER CONSTRUCTION									
			STORMS USED IN ANALYSIS	BASIN CLASS ^{1/}	1966	1967	1968	1969	1970	1971	1972	1973	1974	
Williamsburg Run near Olney	5.83	Nov 1966- Sept 1974	93	LU	3.1	7.6	4.7	3.0	3.3	5.1	7.4	5.1	1.0	
North Branch Rock Creek near Norbeck	25.2	Nov 1966- Sept 1974	92	LR	2.2	3.2	2.0	1.5	1.9	2.2	2.5	2.0	0.5	
Manor Run near Norbeck	2.62	Nov 1966- Aug 1974	71	SU	5.7	10.8	11.8	9.6	7.4	5.4	3.9	0.8	0.9	
Northwest Branch Anacostia River at Norwood	6.35	Mar 1967- Aug 1974	58	LR	0.2	1.1	0.2	0.3	0.4	0.2	0.1	0.9	2.5	
Batchellors Run at Oakdale	1.22	Aug 1967- Aug 1974	26	SR	0.0	1.7	0.7	0.7	0.7	0.3	0.3	0.3	4.0	
Nursery Run at Cloverly	0.91	Apr 1967- Sept 1973	52	SR	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	
Bel Pre Creek at Layhill	4.38	June 1963- Aug 1974	92	LU	14.0	13.9	9.8	11.1	9.7	8.9	13.7	15.2	11.0	
Lutes Run at Lutes	1.22	June 1963- Sept 1974	40	SU	13.3	9.3	4.3	4.3	4.3	1.7	1.7	1.7	0.7	

^{1/} NOTE: L - Drainage area larger than 3.9 km²
 S - Drainage area smaller than 3.9 km²

U - More than 10% of basin area in urban residential and public-commercial land-use categories
 R - Less than 10% of basin area in urban residential and public-commercial land-use categories

distribution of storm rainfall. Suspended sediment was sampled with a combination of automatic single-stage samplers, manual depth-integrating samplers, and automatic pumping samplers, which were used at four sites. The percentage of construction area in the basins was determined from aerial photographs obtained annually between 1966 and 1974 and adjusted for seasonal variations in construction activity.

REGRESSION MODEL

A stepwise multiple regression model was selected to evaluate the effects of the different storm-period variables on sediment loads. In the first step of the regression program, all the variables are included in the computations. In subsequent steps, the variable with the least significant partial-regression coefficient in the preceding equation is eliminated from further computations. The elimination and recomputation continues until one independent variable remains. The final output of the multiple regression model consists of a simple correlation matrix of all selected variables and a series of multiple regression equations for each basin.

From 26 to 93 storms (table 1), depending on the availability of stage, sediment-concentration, and precipitation data, were used in the analysis of the relative effects of selected storm-period variables. A total of 15 variables was determined for each basin studied. These variables are:

- Storm sediment load (S_L) - total load transported during the runoff period, in tons.
- Total runoff (Q_T) - total runoff during days of surface runoff, in $\text{ft}^3/\text{s-d}$ (cubic feet per second-days).
- Storm runoff (Q_s) - total runoff minus estimated baseflow, in $\text{ft}^3/\text{s-d}$.

(Baseflow was estimated as the runoff below a straight line drawn from the point of initial rise to the point where the recession limb of the hydrograph approached a straight line.)
- Peak discharge (Q_p) - instantaneous peak discharge, in ft^3/s (cubic feet per second).
- Antecedent discharge (Q_a) - mean daily discharge the day before the initial rise, in ft^3/s .

- Antecedent days (A_D) - the number of days between storms.
- Total precipitation (R_T) - total precipitation on the drainage basin as determined by isohyetal maps for each storm, in inches.
- Rainfall intensity - maximum rainfall during a given interval as determined by the closest available recording-rain gage:

- R_{05} - maximum 5-min rainfall, in in/hr (inches per hour).
- R_{15} - maximum 15-min rainfall, in in/hr.
- R_{30} - maximum 30-min rainfall, in in/hr.
- R_{1H} - maximum 1-hr rainfall, in in/hr.
- R_{3H} - maximum 3-hr rainfall, in in/hr.

Note. - The 5-min, 15-min, 30-min, and 1-hr rainfall intensities were determined for the Lutes Run basin. The 15-min, 30-min, 1-hr, and 3-hr intensities were determined for the other seven basins.

- Number of Peaks (N_p) - number of peaks during storm.
- Time (T_m) - number of months between the beginning of the record and the storm.
- Construction (C_p) - percentage of basin area under active construction at the time of the storm.
- Peak ratio (P_r) - approximated as:
$$P_r = \frac{Q_p - Q_a}{Q_s}$$

In order to meet the assumptions of a linear regression model, hydrologic data generally must be transformed to logarithms. A review of the study by Guy (1964) and a partial graphical analysis of data used in this study indicated that the following transformations were required: $\log S_i$, $\log Q_s$, $\log Q_p$, $\log (10 \times Q_a)$, $\log (10 \times R_T)$, $\log (10 \times R_{05})$, $\log (10 \times R_{15})$, $\log (10 \times R_{30})$, $\log (10 \times R_{1H})$, $\log (10 \times R_{3H})$, and $\log P_r$. Antecedent runoff and the rainfall factors were multiplied by 10 before conversion to simplify the logarithmic expression of the original values.

CORRELATION MATRICES

Correlation matrices of selected variables for individual stations were examined with three objectives in mind: to investigate the possibility of bias introduced into the regression analysis by changes in sampling procedures or climatic conditions; to determine the degree of relation between sediment load and the independent variables; and to determine the intercorrelation of the independent variables. The relation between time, in months (hereafter referred to as the chronology factor), and the other independent variables was used as an indicator of a climatic or sampling bias during the study period.

Chronology and total storm rainfall exhibit only a low, nonsignificant intercorrelation, indicating that there has been no significant change in the magnitude of the rainfall events used in the regressions. Lutes Run is the only exception, exhibiting a highly significant (99-percent confidence level) negative intercorrelation between chronology and total precipitation. Apparently, more small storms were sampled toward the end of the study period. This probably resulted from an improvement in pumping-sampler hardware and techniques.

While there is a low, nonsignificant intercorrelation between chronology and total storm precipitation, there is generally a positive intercorrelation between chronology and net storm discharge. Intercorrelations are significant at the 95 percent confidence level for Williamsburg Run, Manor Run, and Northwest Branch Anacostia River. These positive intercorrelations are probably related to significant positive intercorrelations between chronology and antecedent discharge, which are a reflection of a trend toward wetter years at the end of the study. This theory is supported by the precipitation records for stations near the project area, which indicate an increase in average annual precipitation of about 250 mm (10 in) during the second half of the sample period. Apparently there were more storms and a shorter time between storms near the end of the project. Therefore, higher soil moisture levels and higher baseflows existed at the onset of many of the later storms.

Lutes Run and Bel Pre Creek, draining the two most extensively urbanized basins in the study area, are the only streams exhibiting significant positive intercorrelation between chronology and peak ratio. This relationship indicates that the ratio of peak discharge to storm discharge has been increasing, probably due to the effects of increased impervious area and storm sewers in these basins. In the Lutes Run basin, the smaller storm size and disproportionate number of summer storms for 1973 and 1974 also contributed to the significant positive correlation between chronology and peak ratio. Summer storms with low runoff volumes generally have a single peak of relatively short duration, resulting in a high peak ratio.

The effect of each independent variable on sediment load was evaluated in subsets to facilitate comparison between basins. Basins were classified as urban or rural and small or large (table 1). Basins with

less than 10 percent of the area in urban residential or public-commercial land-use categories were considered rural, and the others were considered urban. The urban basins generally had active construction sites throughout the study period. Basins were classified as small or large depending on whether the drainage area was less than or greater than 3.9 km^2 (1.5 mi^2).

There was a highly significant positive correlation between sediment load and storm runoff. This is expected since runoff was a component of sediment load computation in this study.

Other variables with a significant positive relation with sediment load are peak discharge, total precipitation, and rainfall intensity. These are significant for all basins--small, large, rural, and urban. The chronology factor and percentage construction are only significant for the urban basins. That there was no significant correlation between chronology and sediment load in the rural basins is further evidence that the sediment data were not biased by changes in sampling or climatic conditions.

The correlation of antecedent discharge, antecedent days, and peak ratio with sediment load differs for large and small basins. Sediment load has a significant positive correlation with antecedent discharge, and a significant negative correlation with antecedent days on the large basins. The correlations are insignificant at the 95 percent confidence level on the small basins. This difference between the large and small basins probably reflects higher correlation between runoff volume and sediment loads on the large basins. The sediment load from small basins is less affected by runoff volume and more dependent on the intensity or peakedness of runoff. This is indicated by a significant correlation between peak ratio and sediment load for the small basins.

A number of independent variables were found to be significantly intercorrelated. The intercorrelations between the various rainfall intensity parameters were highly significant. Correlations between rainfall parameters, peak discharge, and peak ratio were also high. A generally negative intercorrelation exists between antecedent discharge and rainfall intensity. This is apparently a reflection of the seasonal variation of storm types. Intense convective storms usually occur during the growing season when the baseflow is generally lower than during the dormant season. Because of the intercorrelation of these variables, the regression model was set up so that these variables would not be considered simultaneously. As many as ten runs of the model were made for each basin so that the effect of each of these variables could be evaluated without the influence of the other highly correlated independent variables.

REGRESSION EQUATIONS

The computer analyses of various combinations of independent variables produced regression equations of the form

$$\log S_L = b_0 + b_1 x_1 + b_2 x_2 + \dots + b_n x_n$$

where

- S_L = sediment load,
- b_0 = regression constant,
- b_n = regression coefficient for the corresponding variable (X_n).

Each model for an individual station was analyzed and the best equations with one, two, three, and four independent variables were selected based on the multiple correlation coefficient and the standard error of estimate. The regression equations summarized in table 2 are generally consistent with the results of the correlation analyses. Storm runoff is the most significant parameter affecting sediment load. It explained 52 to 72 percent of the variation of sediment load for the 5 sites when it was the most significant independent variable. Peak discharge was the most significant independent variable at three sites: North Branch Rock Creek, Manor Run, and Nursery Run. It explained 40, 83, and 86 percent of the variation of sediment load, respectively. There was no apparent relation between the size of the basin or degree of urban development and the significance of peak discharge in the regression equations. The addition of a second independent variable to the regression equation for each basin generally resulted in a marked improvement in the multiple correlation coefficient and standard error of estimate. This is particularly true in the basins where storm runoff was the most significant independent variable. The addition of the third and fourth independent variables improved the relations to a lesser extent. At stations with few storms available for analysis, the standard error increased with the addition of a fourth independent variable.

The second and third most significant independent variables in the regression equations were generally related to storm intensity. Peak ratio, 15-min rainfall, or 30-min rainfall were selected at all sites except Nursery Run. Either percentage construction or the chronology factor was also selected as the second or third independent variable for most stations. In fact, these were the only factors that showed any difference between the urban and rural streams. Each basin with active construction showed a significant relation between sediment load and percentage construction or the closely related chronology factor.

TABLE 2.--MULTIPLE CORRELATION COEFFICIENTS, STANDARD ERRORS, AND BEST REGRESSION EQUATIONS EXPLAINING STORM-SEDIMENT LOAD VARIATION

NUMBER OF VARIABLES	BEST REGRESSION EQUATION ($\log S_L =$)	MUL. CORR. COEF.	STANDARD ERROR LOG UNITS
Williamsburg Run			
1	$.387 + 1.08 \log Q_s^a$	.84	.304
2	$.051 + 1.03 \log Q_s^a + .45 \log (10 R_{30})^a$	.90	.253
3	$-.166 + .99 \log Q_s^a + .48 \log (10 R_{30})^a + .05 C_p^a$	.91	.240
4	$-.241 + .94 \log Q_s^a + .52 \log (10 R_{30})^a + .04 C_p^b + .13 \log (10 Q_a)^a$	.91	.238
North Branch Rock Creek			
1	$-1.22 + 1.49 \log Q_p^a$	.91	.255
2	$-1.53 + 1.50 \log Q_p^a + .15 C_p^a$	.92	.239
3	$-1.63 + 1.44 \log Q_p^a + .15 C_p^a + .23 \log (10 R_{15})^a$	.93	.223
4	$-1.46 + 1.13 \log Q_p^a + .15 C_p^a + .29 \log (10 R_{15})^a + .30 \log Q_s$	.93	.221
Manor Run			
1	$.334 + .83 \log Q_p^a$	.63	.410
2	$.371 + 1.07 \log Q_p^a - .01 T_m^a$	.84	.288
3	$.385 + 1.24 \log Q_p^a - .01 T_m^a - .32 \log (10 R_{30})^b$	.85	.278
4	$.411 + 1.16 \log Q_p^a - .03 T_m^a - .01 \log (10 R_{30})^b + .09 \log Q_s$	.86	.280

Significant at 99 percent confidence level ^a

Significant at 95 percent confidence level ^b

TABLE 2.--MULTIPLE CORRELATION COEFFICIENTS, STANDARD ERRORS, AND BEST REGRESSION EQUATIONS EXPLAINING STORM-SEDIMENT LOAD VARIATION (Continued)

NUMBER OF VARIABLES	BEST REGRESSION EQUATION ($\log S_L =$)	MUL. CORR. COEF.	STANDARD ERROR LOG UNITS
Northwest Branch Anacostia River			
1	$.530 + .97 \log Q_s^a$	.74	.336
2	$-.522 + 1.19 \log Q_s^a + .88 \log P_r^a$	.84	.274
3	$-.470 + 1.31 \log Q_s^a + .88 \log P_r^a - .004 T_m^a$	.87	.252
4	$-.743 + 1.20 \log Q_s^a + .88 \log P_r^a - .004 T_m^b + .35 \log (10 R_T)$	.87	.250
Batchellors Run			
1	$.049 + 1.18 \log Q_s^a$	.72	.372
2	$-.757 + 1.13 \log Q_s^a + .88 \log P_r^a$	.84	.297
3	$-1.28 + 1.07 \log Q_s^a + .90 \log P_r^a + .44 \log (10 R_T)$	.85	.295
4	$-1.21 + 1.07 \log Q_s^a + .90 \log P_r^a + .44 \log (10 R_T) - .001 T_m$	.85	.300
Nursery Run			
1	$-1.73 + 1.49 \log Q_p^a$	.95	.253
2	$-1.45 + 1.47 \log Q_p^a + .003 T_m^b$	.95	.245
3	$-1.34 + 1.33 \log Q_p^a + .003 T_m^b + .21 \log Q_s$	.96	.242
4	$-1.10 + 1.34 \log Q_p^a + .003 T_m^b + .29 \log Q_s - .22 \log (10 R_T)$	.96	.243

Significant at 99 percent confidence level ^a

Significant at 95 percent confidence level ^b

TABLE 2.--MULTIPLE CORRELATION COEFFICIENTS, STANDARD ERRORS, AND BEST
REGRESSION EQUATIONS EXPLAINING STORM-SEDIMENT LOAD VARIATION (Continued)

NUMBER OF VARIABLES	BEST REGRESSION EQUATION ($\log S_L =$)	MUL. CORR. COEF.	STANDARD ERROR LOG UNITS
Bel Pre Creek			
1	$.458 + 1.12 \log Q_s^a$	.76	.402
2	$-.791 + 1.44 \log Q_s^a + 1.09 \log P_r^a$	.85	.324
3	$-1.09 + 1.31 \log Q_s^a + .97 \log P_r^a + .05 C_p^a$	.91	.256
4	$-.934 + 1.18 \log Q_s^a + .60 \log P_r^a + .05 C_p^a + .28 \log (10 R_{15})^b$	.92	.248
Lutes Run			
1	$.438 + 1.52 \log Q_s^a$	.85	.473
2	$1.37 + 1.05 \log Q_s^a - .01 T_m^a$	.93	.345
3	$.520 + 1.32 \log Q_s^a - .01 T_m^a + .66 \log P_r^a$	.96	.274
4	$.582 + 1.24 \log Q_s^a - .01 T_m^a + .52 \log P_r^a + .14 \log (10 R_{15})$	.96	.277

Significant at 99 percent confidence level ^a
Significant at 95 percent confidence level ^b

SIGNIFICANCE OF REGRESSIONS

The regression equations in table 2 indicate the complex relationship that exists between storm-sediment loads and the factors affecting erosion and sediment transport. As in the study of large Atlantic coast streams (Guy, 1964), storm runoff, rainfall intensity, and individual storm peak ratio significantly affect the sediment load. However, even though a relatively dense network of rain gages was used to determine rainfall amount and intensity, the relationships developed for small basins were no better, and in some cases worse, than the relationships developed for the large basins. The lowest standard error of estimate for the equations in table 2 is 0.221 log units, or about 52 percent. Part of the error is attributable to the inaccuracies inherent in suspended-sediment sampling; however, much of the error is probably attributable to factors not analyzed by the regression model. Factors such as the location of construction areas, cultivated fields, and differing soil conditions, with respect to the distribution of rainfall, must be analyzed before storm-sediment loads can be accurately defined by regression or other modeling techniques.

The regression equations in table 2 indicate the significance of several parameters in affecting storm-sediment loads. Percentage construction or the chronology factor was selected for inclusion in regression equations for each of the basins having more than minimal construction during the study period. This is true in spite of the fact that the amount of construction varied little from year to year within a basin. For example, construction in the North Branch Rock Creek basin varied from 0.5 to 3.2 percent of the basin area, but the percentage construction was the second most significant parameter explaining the variation of storm-sediment loads. This indicates that small amounts of construction can cause substantial increases in the sediment loads of small streams.

The positive correlation between storm-intensity parameters and sediment load should be an important consideration when discussing the control of urban sediment. Rainfall intensity and peak ratio parameters, which were significant in regression equations for 7 of 8 study basins, vary seasonally. Low-intensity rainfall and low peak ratios are associated with frontal storms common in fall, winter, and early spring. High-intensity rainfall and high peak ratio are associated with convective storms common in late spring and summer. As sediment load increases with storm intensity, the impact of construction activities could be reduced in urban streams if construction were limited or strictly controlled in spring and summer.

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WATER AND SEDIMENT ROUTING FROM SMALL WATERSHEDS

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ABSTRACT

In many past studies, a statistical interpretation of observed data has been utilized to solve sediment-yield and related problems. The unit hydrograph method for water routing and the Universal Soil-loss Equation for estimating erosion are examples of these types of studies. It is difficult to predict the response of a watershed to various land developments or treatments using these methods because they are based on the assumption of homogeneity in time and space. Numerical modelling using equations describing the physical processes is a viable way to study the effects of various watershed treatments or land developments on water and sediment yields from watersheds.

The numerical model presented in this paper simulates the physical processes by which water and sediment are moved overland to and down creeks and rivers in watersheds. Some of the processes modeled are interception and infiltration from rainfall, overland flow from excess rainfall, sediment production due to raindrop impact, sheet erosion by overland flow, channel erosion, and the water and sediment routing through the channel system. A nonlinear kinematic-wave approximation for flow routing has been used to route water and sediment overland and in channels.

For the watershed simulated, the computed water and sediment yields agree with the measured water and sediment yields. In addition, this model has the capability to predict watershed treatment effects on individual water and sediment hydrographs and long-term yields, and to identify the sediment sources in watersheds.

INTRODUCTION

The management of watersheds and river basins for the optimum benefit of the people in general requires a complete knowledge of the inter-relations between ecology and environment. The watershed response to developments, either natural or man-induced, must be anticipated correctly if progress is to be made towards wise use of our nation's natural resources.

The physical quantities which describe the major watershed response are the water hydrograph and yield, the sediment hydrograph and yield, and the resultant watershed stream morphology. Because the physical processes governing watershed behavior are very complicated, many past studies have utilized a statistical interpretation of observed watershed response data. The Unit Hydrograph Method for water routing and the Universal Soil-loss Equation for estimating soil erosion are examples of these types of statistical studies.

However, it is difficult to predict the response of a watershed to various land developments or treatments using these methods because they are based on the assumption of homogeneity in both time and space. Numerical modeling using equations describing the physical processes is a viable way to estimate the time-dependent watershed response. In recognition of the necessity of such a model, Simons et al. (1975) has developed a numerical computer program employing the formulation of the basic physical processes to determine water and sediment hydrographs and yields from small watersheds. A brief description on model formulation data needs and test results for the mathematical model developed by Simons et al. (1975) is presented in this paper.

MODEL FORMULATION

Simons et al. (1975) simulated the land surface hydrologic cycle, sediment production, and water and sediment movement on small watersheds. Conceptually the watershed is divided into an overland flow part and a channel system part. Different physical processes are important for the two different environments. In the overland flow loop, processes of interception, evaporation, infiltration, raindrop impact detachment of soil, erosion by overland flow, and overland flow water and sediment routing to the nearest channel are simulated. In the channel system loop, water and sediment contributed by overland flow are routed and the amount of channel erosion or sediment deposition through the channel system is determined. The main functions in the model are shown in Fig. 1.

In the Simons model, emphasis is on the mechanics of water and sediment routing and the model is set up for single storm hydrograph computations. As yet, no attempt has been made to simulate the long-term water balance in the watershed. However, any valid water balance model, such as Stanford Watershed Model IV (Crawford and Linsley, 1966) can be interfaced with the Simons model. The outlines of components in the Simons model are given as follows.

Overland Flow Loop

There are five components in the overland flow loop: interception; infiltration; overland surface water routing; overland subsurface water routing; and overland flow sediment routing.

Interception component: In this component the interception amounts due to the crown and forest floor are computed and the net rainfall is determined from the rainfall input. The interception loss includes the constant interception storage and the continuous evaporation from the interception surfaces. The evaporation is usually negligible during the storm. The interception storage is formulated to be a function of canopy-cover density, groundcover density, and vegetation type. Different storage capacities of interception due to the tree crown and the forest floor result in different rates of net rainfall in areas under canopy and in areas without trees.

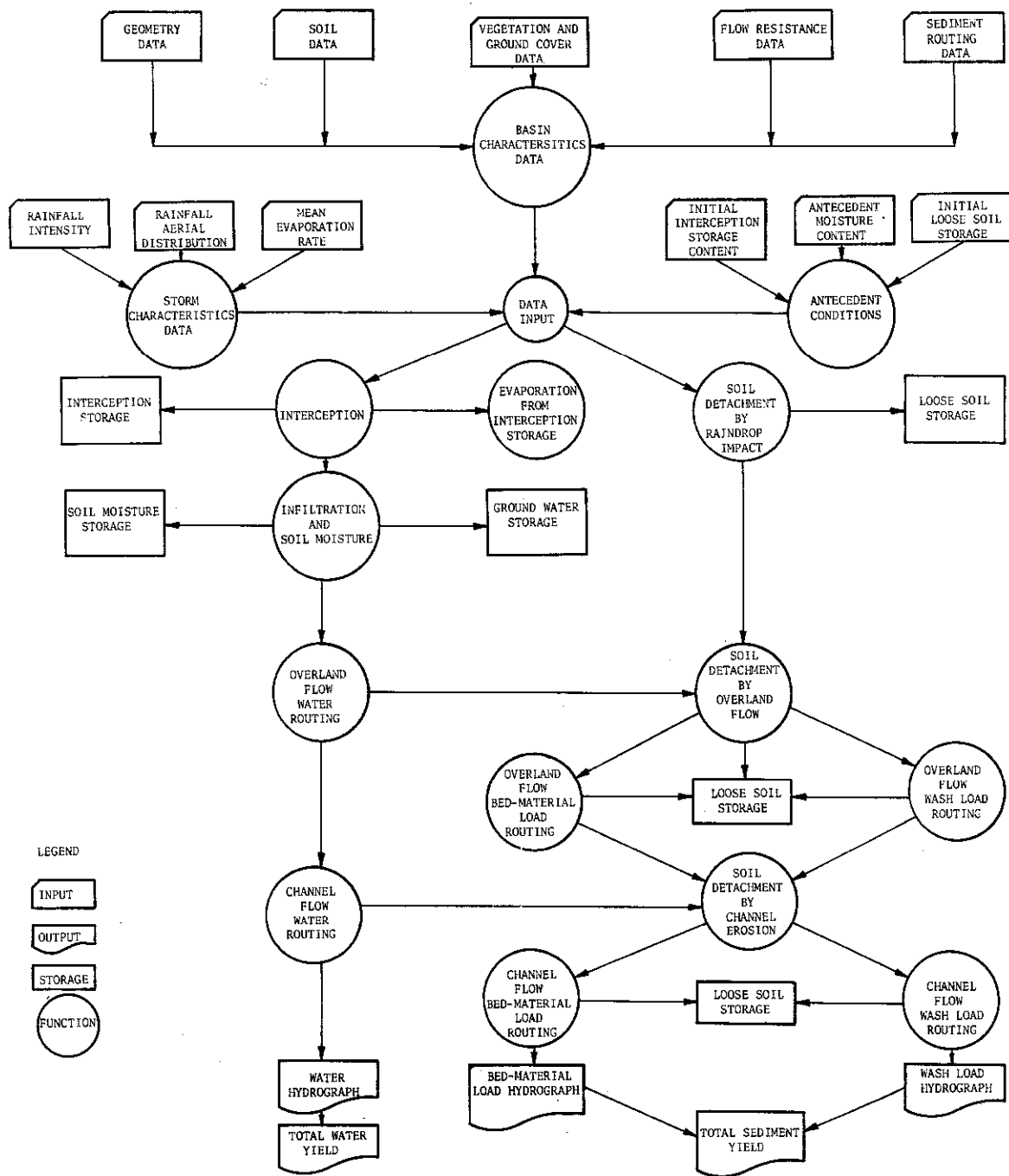


Fig. 1. Flow chart for the water and sediment routing model.

Infiltration component: This component of the model simulates the process of infiltration. Due to the different rate of net rainfall under canopy as compared to an open area without trees, the infiltration rate is simulated at a point under the canopy and at another point in the open. The infiltration rate at each typical point is computed by an approximation of Darcy's Law assuming that a distinct wetting front exists and it is formulated to be a function of saturated hydraulic conductivity, average capillary suction pressure, soil porosity, antecedent moisture content, and moisture content in the wetted zone. The rate of rainfall excess can thus be determined from the net rainfall and infiltration rates. A weighting function is then introduced to obtain a mean rate of rainfall excess. This weighting function is expressed in terms of canopy cover density.

Overland surface water routing component: With this component the overland surface water runoff resulting from the mean rainfall excess is routed to the nearest channel. The routing procedure is based on the continuity of water, a momentum equation of kinematic wave approximation, and a set of resistance functions for different hydraulic conditions. The total resistance to flow is assumed to be a sum of the drag resistance due to ground cover and the shear stress acting on the soil bed. The effect of rainfall on the resistance to flow is also taken into account for small Reynolds number flow. The computation is carried out utilizing a nonlinear finite difference scheme developed by Li et al. (1975) and the computation results include the mean flow depth, bed shear stress and flow discharge at computation points as a function of time and space.

Overland flow sediment component: This component of the model computes the amount of soil detachment by raindrop splash and by overland flow, the amount of wash load pickup and transport by surface runoff, and bed-material load movement. The amount of soil detachment by raindrop splash is assumed to be a simple power function of rainfall intensity. It is assumed that the amount of soil detachment by raindrop splash is negligible if the soil surface is covered by coarser soil material that provides an armoring effect. The soil detachment by surface runoff is considered as the result of bed-material load movement. The local transporting capacity of bed-material load is assumed to be a function of local effective bed shear stress, and a combination of Meyer-Peter-Müller bed load equation (USBR, 1960) and the Einstein suspended load procedure (Einstein, 1950) is the sediment transport equation. The wash load pickup rate is formulated to be a function of bed shear stress and the available amount of loose soil. The sediment routing procedure is primarily based on the continuity equation for sediment (wash load and bed-material load). The computation is carried out utilizing a finite difference numerical procedure coupled with the overland surface water routing.

Channel System Loop

The channel system loop routes water and sediment contributed from all overland flow areas through the channel system, and computes degradation and aggradation in the channels.

Channel water routing component: This component of the model routes the water down the creeks in the channel system and computes the hydrograph at the watershed outlet. The lateral water inflows to the channel system are the overland surface water flows. The channel water routing procedure and the finite difference scheme are similar to those used in the overland flow loop.

Channel sediment routing component: With this component, the wash load and bed-material load are routed through the channel system. The computation results include the wash load and bed-material load hydrographs and the total sediment yield at the watershed outlet. The procedures of routing wash load and bed-material load are similar to those used in the overland flow sediment routing. The amount of degradation and aggradation in the channel system is determined by using the continuity equation for sediment.

MODEL INPUT DATA

The input required for the Simons model are summarized as follows:

Geometry Data

These data include the slope length, bed slope, and wetted perimeter versus flow area relations.

Soil Data

These data include the saturated hydraulic conductivity, average capillary suction pressure, soil porosity, degree of saturation in the wetted zone and particle size distribution.

Vegetation and Ground Cover Data

These data include canopy cover density, ground cover density in overland flow units and in channel units, the average height of low ground cover density in channels, the interception storage capacity of ground cover, the ratio of evaporating surface to the horizontal projected area for ground cover, and the ratio of the interception storage capacity of a tree canopy to the interception storage capacity of the ground cover.

Flow Resistance Parameters

These parameters include constants describing grain resistance for different Reynolds numbers, the constant representing added roughness due to raindrop impact, and values for the overland flow ground-cover resistance descriptor, and channel-flow ground-cover resistance descriptor.

Sediment Routing Parameters

These parameters include constants describing the sediment transporting capacity, the maximum penetration depth of raindrop impact, the parameters describing the potential soil detachment rate and the detachment coefficient of soil by surface runoff (soil erodibility).

Storm Characteristics

These data include rainfall intensity, aerial distribution of rainfall intensity, and the mean evaporation rate.

Antecedent Conditions

These data include the initial interception storage content, the antecedent soil moisture content, and the initial loose soil storage.

SIMULATION RESULTS

Simons et al. (1975) tested the applicability of their model on the Beaver Creek Watershed, Arizona. Five runoff events in Watershed 1 and one runoff event in Watershed 17 were used.

Watershed 1 is a small drainage catchment with an area of 313.6 acres that has been clear-cut. The five storm events in Watershed 1 used in this study area occurred on November 22, 1965, November 24, 1965, November 25, 1965, September 6, 1967, and September 5, 1970. The latter was a large event and is known as the "Labor Day" storm.

Watershed 17 has an area of 287.4 acres. The only storm available for testing is the "Labor Day" storm of September 5, 1970. The model calibration was based on this storm on Watershed 17.

An example of the comparison between the simulated and the measured water hydrographs is shown in Fig. 2. The agreement between the measured and the simulated water hydrographs is, in the most part, satisfactory. Because there is no measured sediment hydrograph, no comparison can be made. Other comparisons on water yield, peak water flow, time to peak water flow, and sediment yield are given respectively in Fig. 3. This figure shows that the water and sediment routing model simulated the shape, volume, peak flow, and time to peak flow of the six water hydrographs, and the sediment yield from Watershed 1 and Watershed 17 within approximately 30 percent. Satisfactory results were obtained for different size storms and in different watersheds by using only one set of model parameters. This verifies that the model could be used to synthesize missing data and to predict the response of watersheds to various types of watershed management practices. Also, it has been demonstrated that the model could be used to estimate flood flows from ungaged watersheds.

The transferability of the model is one of the main advantages of this physical process simulation model over the conventional methods such as the Unit Hydrograph and Universal Soil-loss equation. For example, the Labor Day (September 5, 1970) storm produced approximately 2.2 times the surface runoff in Watershed 17 than in Watershed 1, but only

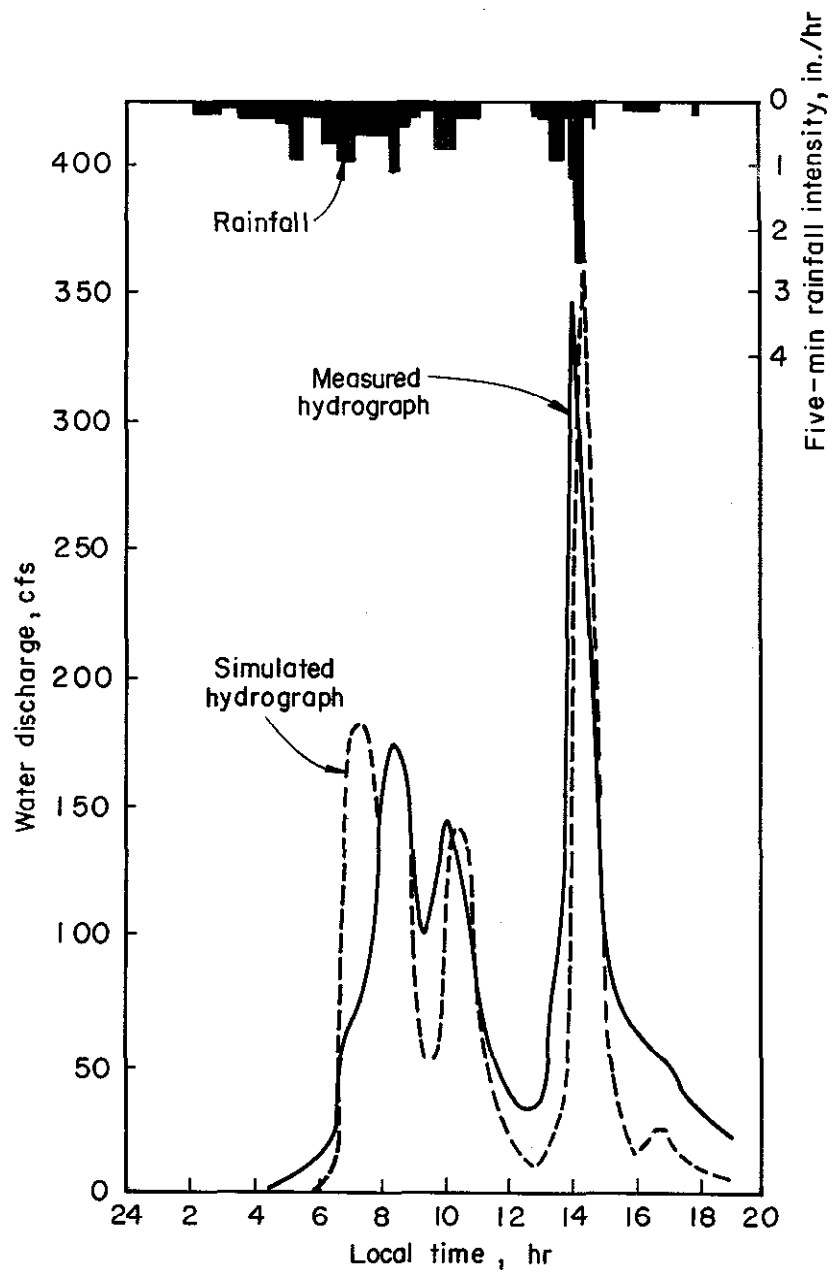


Fig. 2. Water hydrograph from watershed 17 for the September 5, 1970 storm (after Simons et al. 1975).

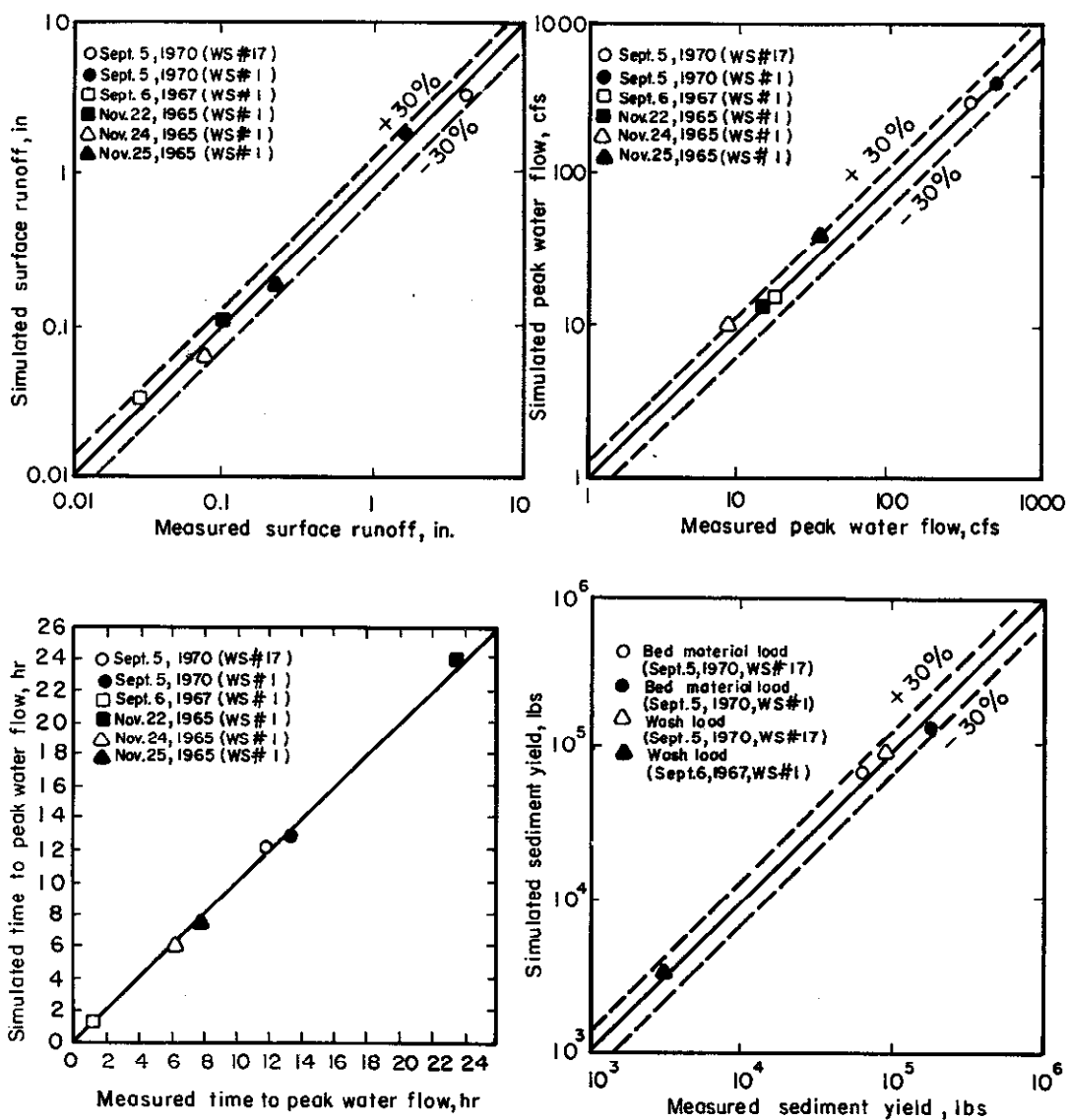


Fig. 3. Comparison of measured and simulated results (after Simons et al. 1975).

about 0.4 times the yield of sediment. There was more surface runoff and less sediment yield in Watershed 17 because it is longer and narrower and its average slope is less than in Watershed 1.

An important aspect in watershed management is to predict watershed treatment effects. The vegetation treatment effects on water and sediment yields are estimated by changing the canopy cover density and the ground cover density in overland flow units. Based on the storms of September 5, 1970 and September 6, 1967, the effects of vegetation treatment on the water and sediment yields from Watershed 1 have been evaluated. As shown in Figs. 4 and 5 for a constant and undisturbed ground cover of 65 percent, water yield, sediment yield and the peak flow rates from these two storms are increased as the canopy cover density is decreased.

The reduction in interception caused by removing the vegetation results in an increase of excess rainfall and loose soil detachment. These effects are much more pronounced in Watershed 1 for the smaller size of storm than for large storms like the Labor Day storm.

The time to peak flow is shortened as the canopy cover is decreased for the small storm but there is no change in time to peak flow for the large storm.

If a watershed is clear-cut and the forest litter, tree mulch, rocks, etc. are also removed in different degrees, or if the ground cover is seriously destroyed by a burning treatment, the associated response can be estimated by changing the ground cover density in overland flow units. The changes in water and sediment yields in Watershed 1 for the storms of September 5, 1970 and September 6, 1967 are shown in Figs. 4 and 5. As the ground cover is decreased, the total surface runoff and peak water flow are increased moderately, the sediment yield and peak sediment flow are increased greatly and the time to peak flow shortened slightly. The effect on water yield is more pronounced for a smaller storm but nearly the same effects on sediment yield are obtained for both small and large storms.

As illustrated above, the ground cover density is an important factor in controlling sediment yield. If a watershed is under the clear-cut treatment but there is a proper management of ground cover, the sediment yield may not be increased.

SUMMARY

A mathematical model simulating water and sediment hydrographs from small watersheds has been developed. This model is designed to simulate the response of the basin to individual storms. The model includes a water balance on the single storm basis, loose soil detachment by raindrop impact and by moving water, and water and sediment routing features for both overland flow and channel systems. The flow routing is accomplished by employing the nonlinear kinematic-wave approximation developed in this study.

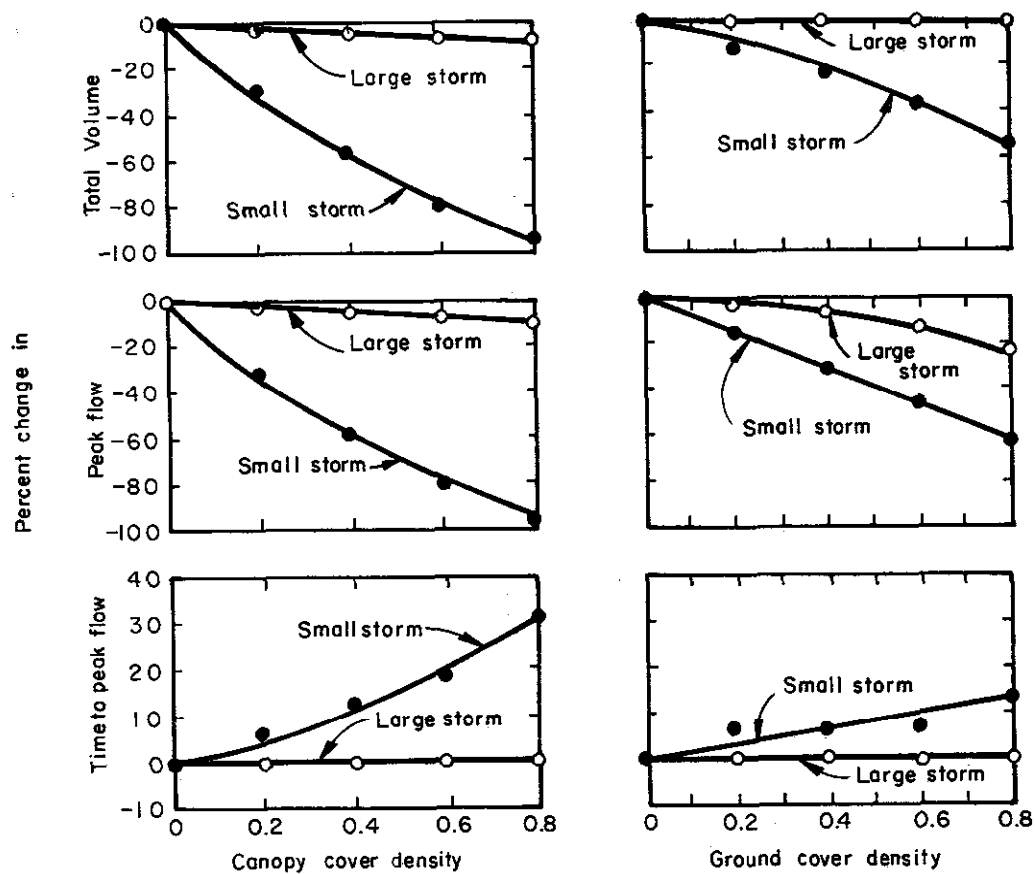


Fig. 4. Effect of canopy cover density and ground cover density on the water yield from watershed 1 (after Simons et al. 1975).

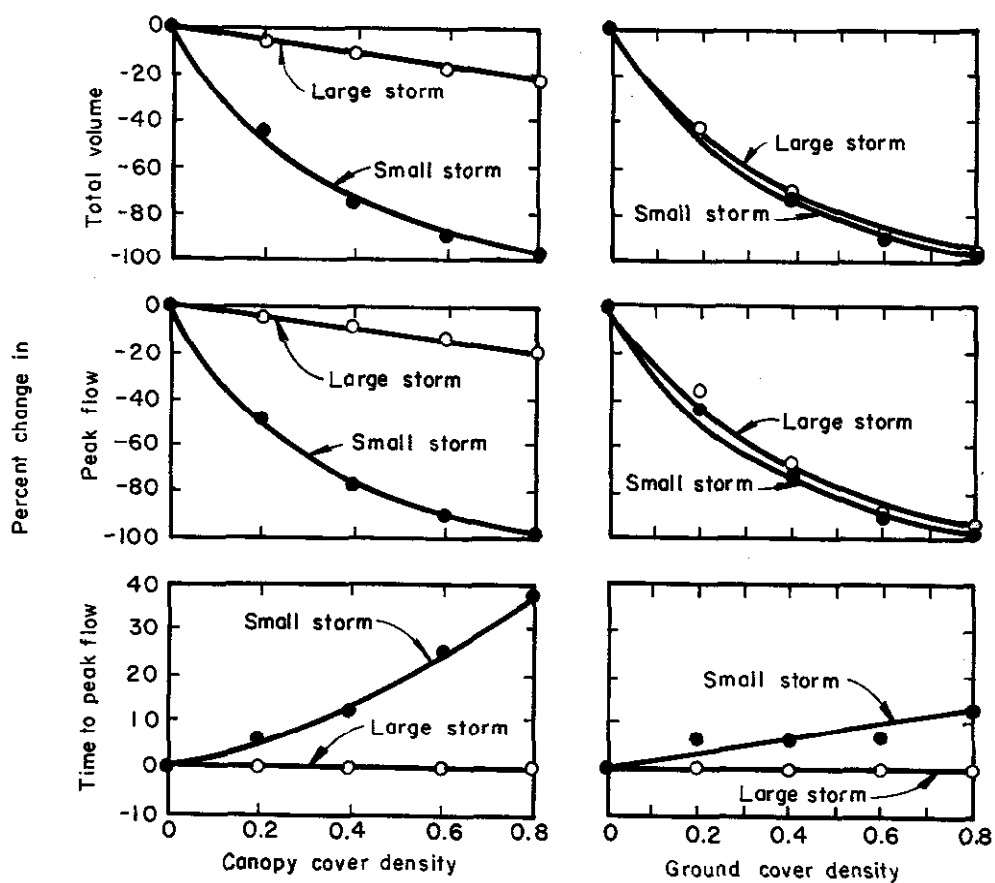


Fig. 5. Effect of canopy cover density and ground cover density on the sediment yield from watershed 1 (after Simons et al. 1975).

The model has been validated with data from Watershed 1 and Watershed 17 in the Beaver Creek drainage of north-central Arizona. With the model, the shape, peak flow and time to peak flow of water and sediment hydrographs along with the total water yield and sediment yield were simulated.

In view of the mathematical approximations made in formulating this water and sediment routing model, the applicability of the model at present is limited to the following situations:

1. The streams within the watershed are ephemeral, and the movement of subsurface flow and ground water flow are negligible.
2. The kinematic-wave approximation for flow routing is valid; i.e., the gradients due to local and convective accelerations are negligible and the water surface slope is nearly equal to the bed slope.
3. The water yield simulation is on the single storm basis.

When a water balance model for simulating the water budget during interstorm periods is incorporated, long-term water and sediment yields can be estimated with this model.

Test results show that there are satisfactory agreements between the simulated and the measured peak water flow; time to peak water flow, water yield and sediment yield for different size storms in two watersheds using only one set of model parameters. This verifies that the model can be used to synthesize missing data and to predict the response of watersheds to various types of watershed management practices. Also, it has been demonstrated that the model could be used to estimate flood flows from ungaged watersheds.

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PREDICTION OF SEDIMENT YIELDS IN WISCONSIN STREAMS

By S. M. Hindall

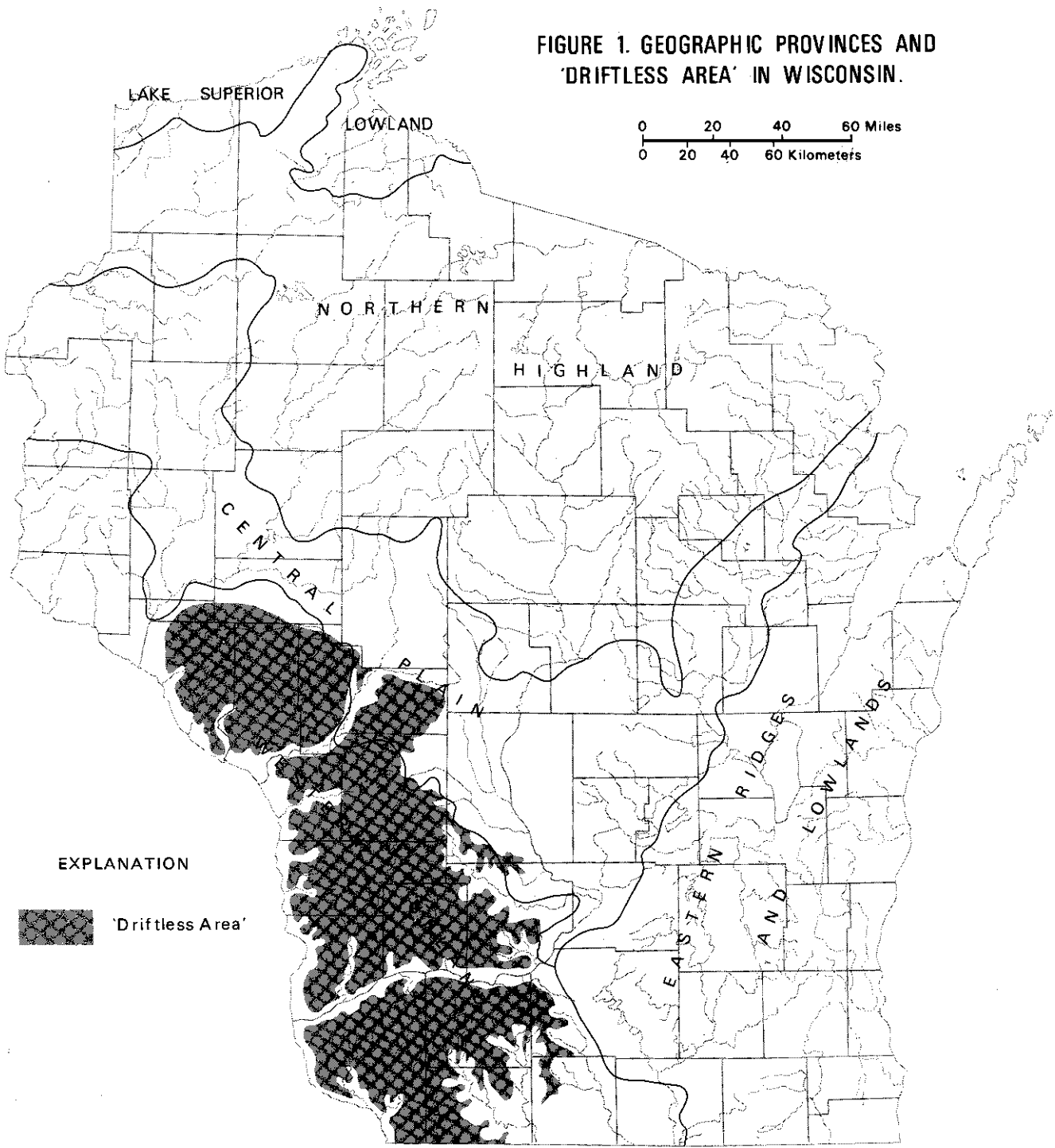
A method has been developed to predict sediment yields at any point on 95 percent of Wisconsin streams. The procedure is simple and requires only data that are readily available. It consists of equations that relate sediment yield to the geographic or physical factors that control sediment production and transport. The equations were developed through regression techniques using physical factors such as topography, soils, land use and cover, stream hydraulics, and climate as independent variables and sediment yield as the dependent variable. The equations are only valid for areas in which the geography is similar to that of Wisconsin, but the procedure used to develop the predictive equations may be applicable in any area where there is sufficient sediment-yield data.

Geography is important in explaining difference in sediment yield between areas. Most of the physical factors that control sediment yields of streams are in some way related to geography. Physical factors such as geology, topography, soils, land use and cover, stream hydraulics, and climatic conditions all have a direct effect on sediment yields but are also all part of the geography of an area. The State has been divided into five geographic provinces, as shown in figure 1 (Martin, 1932, p. 33). The "Driftless Area" of southwestern Wisconsin (Thwaites, 1956) (fig. 1) provides an additional geographic division. This is an area of the State that was not glaciated during Pleistocene time and that has very distinct surface features. This division makes it possible to group streams according to geography, therefore lessening geographic differences between streams. Equations for predicting the sediment yields within each geographic division were developed by regression techniques that relate sediment yields to the physical factors that control sediment production and transport.

The regression equations were developed through a three-step procedure. The first step was selecting and grouping the stations to be used in the analysis. Only stations with drainage areas less than 1,000 mi² (2,590 km²) and with a well defined sediment discharge-stream discharge curve over the entire range of discharge were used. The 60 stations that met these requirements were then grouped according to their geographic province or geologic area. Next, the geographic factors that control sediment yield in each stream were defined, measured, and entered into the regression analysis as independent variables. The 14 factors used for this regression analysis were drainage area, average discharge, 2-year recurrence-interval flood, 25-year recurrence-interval flood, main-channel slope, lake and marsh area, main-channel length, percentage forest cover, soil index, precipitation-intensity index, flood runoff, vegetative factor, mean frost depth, and duration factor. (See appendix 1 for definitions of the variables.) The dependent variable used in the regression analysis was the previously calculated suspended-sediment yield shown as observed yields in table 1.

The final step was the computation of the regression equations by computer. The results of the computer analysis were examined to determine the most significant independent variables and best equation for each province or area. In the four regression equations developed for Wisconsin streams, the number of statistically significant independent variables ranged from 1 in the equation

FIGURE 1. GEOGRAPHIC PROVINCES AND
'DRIFTLESS AREA' IN WISCONSIN.



Geographic provinces from Martin, 1932,
and geology from Thwaites, 1956

Table 1.--Observed versus computed average annual long-term suspended-sediment yields.

Station number	Average annual suspended-sediment yields (tons/mi ²)	
	Observed	Computed
Northern Highland Province		
04025500	9.6	7.2
04026870	10.0	10.0
04061000	10.0	9.9
04063700	3.3	4.8
04066500	6.9	6.6
04071000	3.1	6.7
05359500	3.8	4.1
05362000	8.9	6.5
05393500	8.1	6.6
05394500	8.5	5.3
05397500	7.8	8.9
05399500	31	32
Central Plain Province		
04078500	8.1	9.3
04080000	30	36
04081000	31	21
05368000	29	30
05370000	18	17
05381000	50	47
05401050	34	34
05402000	15	17
05403500	20	22
05403630	9.4	12
05403700	16	12
Eastern Ridges and Lowland Province		
04071858	17	18
04073050	15	19
04085200	16	23
04085281	17	17
04086000	62	47
04086150	11	9.5
04086340	10	9.7
04086360	18	12
04086500	45	44
04087000	8.5	14
04087120	53	29
04087204	38	40
04087220	19	17
04087240	47	76

Table 1.--Observed versus computed average annual long-term
suspended-sediment yields--continued

Station number	Average annual suspended-sediment yields (tons/mi ²)	
	Observed	Computed
Eastern Ridges and Lowland Province--continued		
04087257	81	76
05424000	18	18
05426000	40	41
05431500	12	17
05436500	44	34
05543830	2.7	2.7
"Driftless Area"		
05379500	450	423
05381350	130	105
05382500	270	367
05386500	380	373
05387000	400	540
05387100	680	540
05405000	62	69
05406500	34	29
05408000	280	230
05409890	204	185
05410500	410	503
05413500	636	419
05415000	180	187
05432500	178	188
05433000	140	150
05433500	76	100
05436000	39	43

for the Northern Highland province to 9 for the equation for the Eastern Ridges and Lowland province. The independent variables that were not statistically significant were not included in the equations shown in table 2.

The regression equations, relating sediment yield to physical factors that control sediment yield, are in the form

$$Q_s = a \cdot A^{b_1} \cdot Q_a^{b_2} \cdot Q_{25}^{b_3} \cdot S^{b_4} \dots$$

where "Q_s" is a statistical sediment yield; "A", "Q_a", "Q₂₅", and "S" are sediment-yield controlling factors as defined in appendix 1; "a" is the regression constant; and "b₁", "b₂", "b₃", and "b₄" are coefficients obtained by regression. In the regressions presented in this report the computer calculated the regression equation, the standard error of estimate, and the significance of each geographic factor.

Table 2.--Equations for prediction of suspended-sediment yield.

Number	Equation	Geographic province	Standard error of estimate (percent)	Level of statistical significance (percent)
1	$Q_s = 51.1 \cdot St^{-0.72}$	Northern Highland	35	99
2	$Q_s = 2.82 \cdot 10^{10} \cdot Q_a^{1.43} \cdot Q_{25}^{0.43} \cdot L^{-3.29} \cdot Si^{-3.26} \cdot I^{-1.52}$	Central Plain and glaciated Western Upland	29	95
3	$Q_s = 4.37 \cdot 10^{-12} \cdot Q_a^{2.63} \cdot Q_2^{-5.83} \cdot Q_{25}^{5.92} \cdot S^{-1.94} \cdot L^{-2.52} \cdot Ro^{1.31} \cdot Si^{-6.35} \cdot Fd^{8.26} \cdot D^{0.59}$	Eastern Ridges and Lowlands	38	99
4	$Q_s = 197.7 \cdot A^{2.38} \cdot Q_a^{-3.14} \cdot S^{2.01} \cdot St^{0.19} \cdot L^{4.14} \cdot Fd^{-4.48} \cdot D^{-1.43}$	"Driftless Area" (Unglaciated Western Upland)	28	99

A principal measure of the accuracy of the regression analysis, hence the accuracy with which sediment yield can be estimated, is the statistical measure of error, "standard error of estimate". Even though standard error is only a measure of the accuracy of a regression equation, not an actual sedimentation measuring method, it represents the accuracy of an estimated sediment yield using the regression equation at an ungaged site. It is the estimated limit above and below the average within which about 67 percent of future sediment-yield values are expected to fall. Conversely, there is only one chance in three that future values will differ from the average by more than one standard error.

The regression equations, 1 through 4, standard error of estimate, and statistical significance for four geographic provinces of the State are shown in table 2. The computed versus measured sediment yields of streams in these four geographic provinces are given in table 1. There is no regression equation available for the Lake Superior Lowland province because enough data were not available to run a regression. In this area of the State other methods of estimating sediment yield must be used. The "Driftless Area" and Western Upland province have roughly similar boundaries except for the small glaciated part of the Western Upland province. The effects of glaciation or lack of glaciation created two distinct geographic areas, which are treated as such. To predict sediment yields in that part of the Western Upland province outside the "Driftless Area", regression equation 2 for the Central Plain province is applicable and gives very good results.

Different combinations of the 14 independent variables were found to be statistically significant for each of the four regression equations. The only significant independent variable in the equation for the Northern Highland province was percentage lake and marsh area. The remaining 13 variables used in the analysis were found to be statistically insignificant. The average discharge, 25-year recurrence-interval flood, main-channel length, soil index, and precipitation-intensity index are the only independent variables that were statistically significant in the equation for the Central Plain province. The remaining nine variables were disregarded. In the equation for the Eastern Ridges and Lowland province the average discharge, 2- and 25-year recurrence-interval floods, main-channel slope, main-channel length, 10-year runoff, soil index, frost depth, and duration factor are the significant independent variables. Five remaining variables were found to be statistically insignificant for this province. The equation for the "Driftless Area" had seven statistically significant independent variables: drainage area, average discharge, main-channel slope, percentage lake and marsh area, main-channel length, frost depth, and duration factor. The remaining seven independent variables were insignificant and were not included in the equation.

These regression equations make it possible to predict sediment yields for about 95 percent of Wisconsin streams. Use of the sediment-yield equations is illustrated below by a practical application to the Manitowoc River at Lake Michigan.

1. Determine from figure 1 the major geographic province of the Manitowoc River. In this example it falls completely in the Eastern Ridges and Lowland province and therefore equation number 3 is applicable. Equation number 3 is as follows:

$$Q_s = 4.37 \cdot 10^{-12} \cdot Q_a^{2.63} \cdot Q_2^{-5.38} \cdot Q_{25}^{5.92} \cdot S^{-1.94} \cdot L^{-2.52} \cdot Ro^{1.31} \cdot Si^{-6.35} \cdot Fd^{8.26} \cdot D^{0.59}$$

2. To calculate average discharge (Q_a), in cubic feet per second, first determine the size of the contributing drainage area (A) from the best maps available. For the Manitowoc River it is about 530 mi² (1,373 km²). Next, estimate the average runoff for the basin from figure 2. (See appendix.) In this example it is about 7.5 in (19 cm). Finally, multiply the drainage area by the average runoff and apply the necessary conversion factor (0.074) to get average discharge.

$$Q_a = 7.5 \cdot 530 \cdot 0.074 = 290 \text{ ft}^3/\text{s} \text{ (} 8.21 \text{ m}^3/\text{s) }$$

3. Compute the 2-, 10-, and 25-year recurrence-interval floods (Q_2 , Q_{10} , Q_{25}) from previously developed equations (Conger, 1971). (The 10-year recurrence-interval flood will be used in a later step.) For the Manitowoc River they are as follows:

$$Q_2 = 3,900 \text{ ft}^3/\text{s} \text{ (} 110 \text{ m}^3/\text{s) and}$$

$$Q_{25} = 8,100 \text{ ft}^3/\text{s} \text{ (} 229 \text{ m}^3/\text{s) .}$$

4. Determine the main-channel length (L) and slope (S) from topographic maps, as follows: (a) Measure the river length from the desired location to the basin divide. If the stream forks, follow the fork with the greatest drainage area. This is channel length (L). (b) Determine altitudes at points that are 10 and 85 percent of the total river length. (c) Determine the difference between these altitudes and divide by the distance, in miles, between these points. The Manitowoc River is approximately 70 mi (113 km) long and has a slope of about 5 ft/mi (0.95 m/km).

5. The 10-year runoff (Ro) is calculated by dividing the Q_{10} by the drainage area from step 1.

$$Q_{10} = 6,500 \text{ ft}^3/\text{s} \text{ (} 184 \text{ m}^3/\text{s) and}$$

$$A = 530 \text{ mi}^2 \text{ (} 1,373 \text{ km}^2 \text{) .}$$

For the Manitowoc River it is approximately 12 (ft³/s)/mi² [0.13 (m³/s)/km²].

6. The soil index figure (Si) of 2.90 in (7.4 cm) for the Manitowoc River was determined by the U.S. Department of Agriculture, Soil Conservation Service, upon request.

7. Frost depth (Fd) for the Manitowoc River is determined from figure 5 and is about 24 in (61 cm). (See appendix.)

8. The duration term (D) was determined through a correlation procedure with nearby U.S. Geological Survey continuous-record stations. The Manitowoc River is between the Kewaunee and Sheboygan Rivers, both of which have continuous-record gaging stations. By comparing the hydrologic and geographic characteristics of all three basins, an estimate of 23 was made for the duration term for the Manitowoc River.

9. The final step in the example is substituting the calculated or estimated factors in equation number 3 and performing the necessary calculations. For the Manitowoc River the final equation is:

$$Q_s = 4.37 \cdot 10^{-12} \cdot 290^{2.63} \cdot 3,900^{-5.83} \cdot 8,100^{5.92} \cdot 5^{-1.94} \cdot 70^{-2.52} \\ \cdot 12^{1.31} \cdot 2.9^{-6.35} \cdot 24^{8.26} \cdot 23^{0.59}$$

$$Q_s = 9.88 \cdot 10^1$$

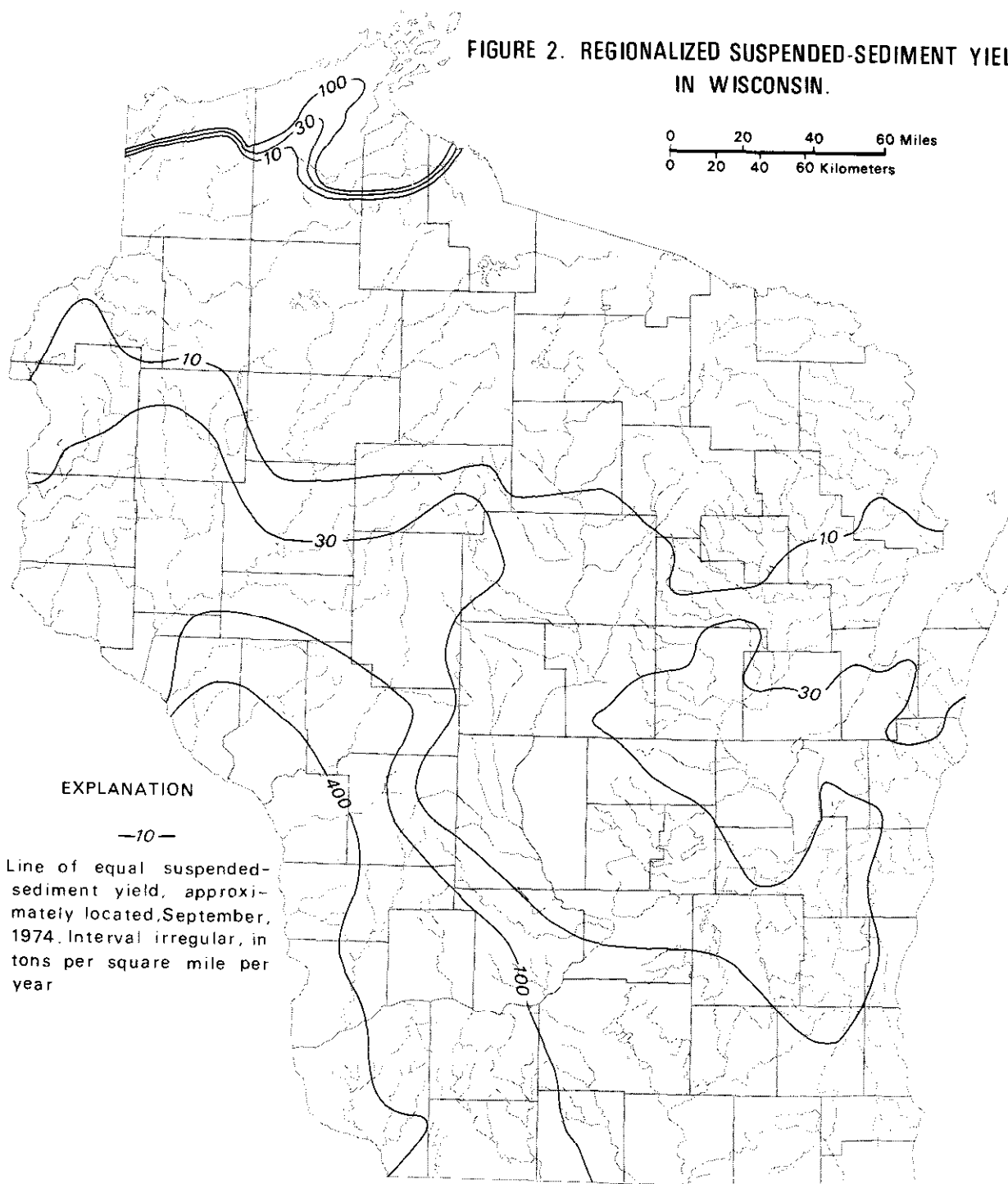
Solving the equation gives an estimated average annual suspended-sediment yield for the Manitowoc River of 99 tons/mi² (35 tonnes/km²). This calculated yield appears to be somewhat high when compared to the regionalized sediment-yield map, which is based on field data, (fig. 2), but the map shows that Manitowoc River sediment yield could range from 30 to 100 tons/mi² (11 to 35 tonnes/km²). Considering that equation number 3 had 38 percent standard error of estimate, the calculated yield and the yield map are in good agreement.

These equations are only a first step in developing models for prediction of sediment yields. As additional data become available and new statistical techniques are developed, more accurate and quicker procedures for prediction of sediment yields and even erosion and deposition rates should become available.

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FIGURE 2. REGIONALIZED SUSPENDED-SEDIMENT YIELD
IN WISCONSIN.



Appendix 1

Dependent variable

1. Sediment yield (Q_s), expressed in tons per square mile per year, is the average amount of dry weight of suspended sediment that passes a stream section during 1 year divided by the area of the drainage basin.

Independent variables

1. Drainage area (A), in square miles, of a stream at a specified location is that area, measured in a horizontal plane, enclosed by a topographic divide from which direct surface runoff from precipitation normally drains by gravity into the stream above the specified point. Drainage areas have been determined for many basins in Wisconsin (Holmstrom, 1972).

2. Average discharge (Q_a), in cubic feet per second, is the arithmetic average of daily mean discharges for a period of years. It can be estimated from the drainage area and average runoff of the basin (fig. 3).

3. Two-year flood (Q_2), in cubic feet per second, is the discharge of a flood that has a recurrence interval of once in 2 years. Regression techniques are available to determine Q_2 for any stream in the State (Conger, 1971).

4. Twenty-five year flood (Q_{25}), in cubic feet per second, is the discharge of a flood that has a recurrence interval of once in 25 years. Regression techniques are available to determine Q_{25} for any stream in the State (Conger, 1971).

5. Main-channel slope (S), in feet per mile, is the slope of the stream between points that are 10 and 85 percent of the distance along the channel from the site where yields are to be determined to the basin divide. It can be determined from U.S. Geological Survey quadrangle maps.

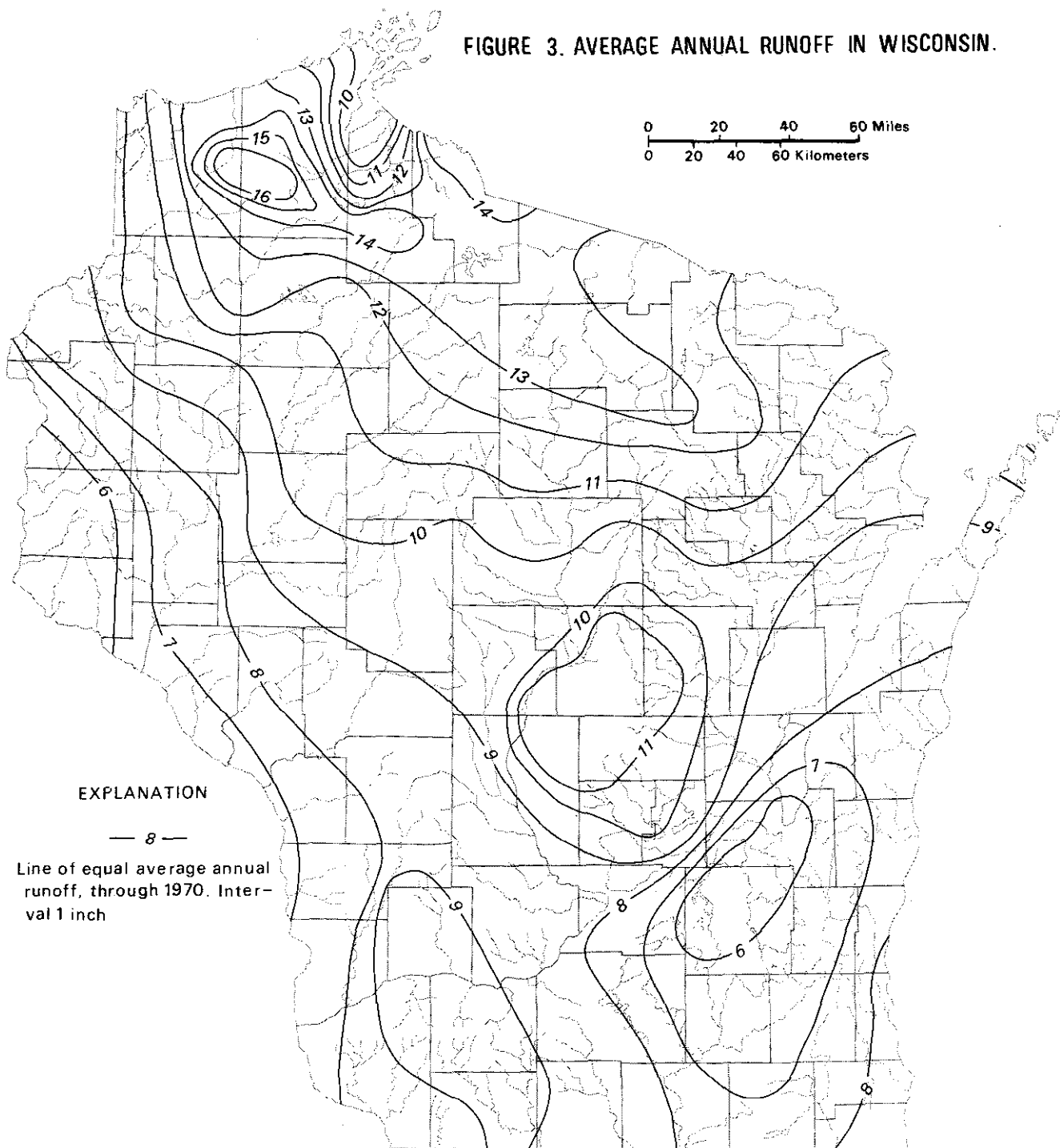
6. Lake and marsh area (St), expressed as percentage of the drainage area, includes lakes, ponds, and wetlands determined from U.S. Geological Survey quadrangle maps and U.S. Department of Agriculture, Soil Conservation Service, data. To avoid zero values, a constant of 1 percent is added to each value to obtain the value of St to be used in the regression equation.

7. Main-channel length (L), in miles, is measured from the site where yield is to be determined to the basin divide. It can be determined from U.S. Geological Survey quadrangle maps.

8. Forest cover (F), expressed as a percentage of the basin drainage area as shown on U.S. Geological Survey quadrangle maps and data from the U.S. Department of Agriculture, Soil Conservation Service. To avoid zero, a constant of 1 percent is added to each value to obtain the value of F used in the regression equation.

9. Soil index (Si), in inches, is an index of soil infiltration capacity. It is available from and calculated by the U.S. Department of Agriculture, Soil Conservation Service, from information on soil type, vegetal cover, and agricultural practices (R. W. Akeley, written commun., 1974).

FIGURE 3. AVERAGE ANNUAL RUNOFF IN WISCONSIN.



10. Precipitation-intensity index (I) (2-year, 24-hour rainfall), expressed in inches, is determined from figure 4 (Hershfield, 1961). This maximum 24-hour rainfall has a recurrence interval of once in 2 years.

11. Flood runoff (R_o), in cubic feet per second per square mile, is the flood discharge that has a recurrence interval of once in 10 years, Q_{10} , divided by the drainage area of the basin. Drainage area data are from variable 1 above, and the flood data can be determined as in variables 2, 3, and 4 above.

12. Vegetative factor (V), in inches per degree F, is the mean annual precipitation divided by mean annual temperature and may be determined from maps available from the Wisconsin Statistical Reporting Service (1967).

13. Mean frost depth on February 28 (F_d), 1961-68 average in inches, is determined from figure 5 (Wisconsin Statistical Reporting Service, 1970, p. 13).

14. Duration factor (D) is the stream discharge that can be expected to occur at least 10 percent of the time divided by the discharge that can be expected to occur 90 percent of the time. Duration data are available from stream-gaging records.

FIGURE 4. PRECIPITATION INTENSITY INDEX IN WISCONSIN.

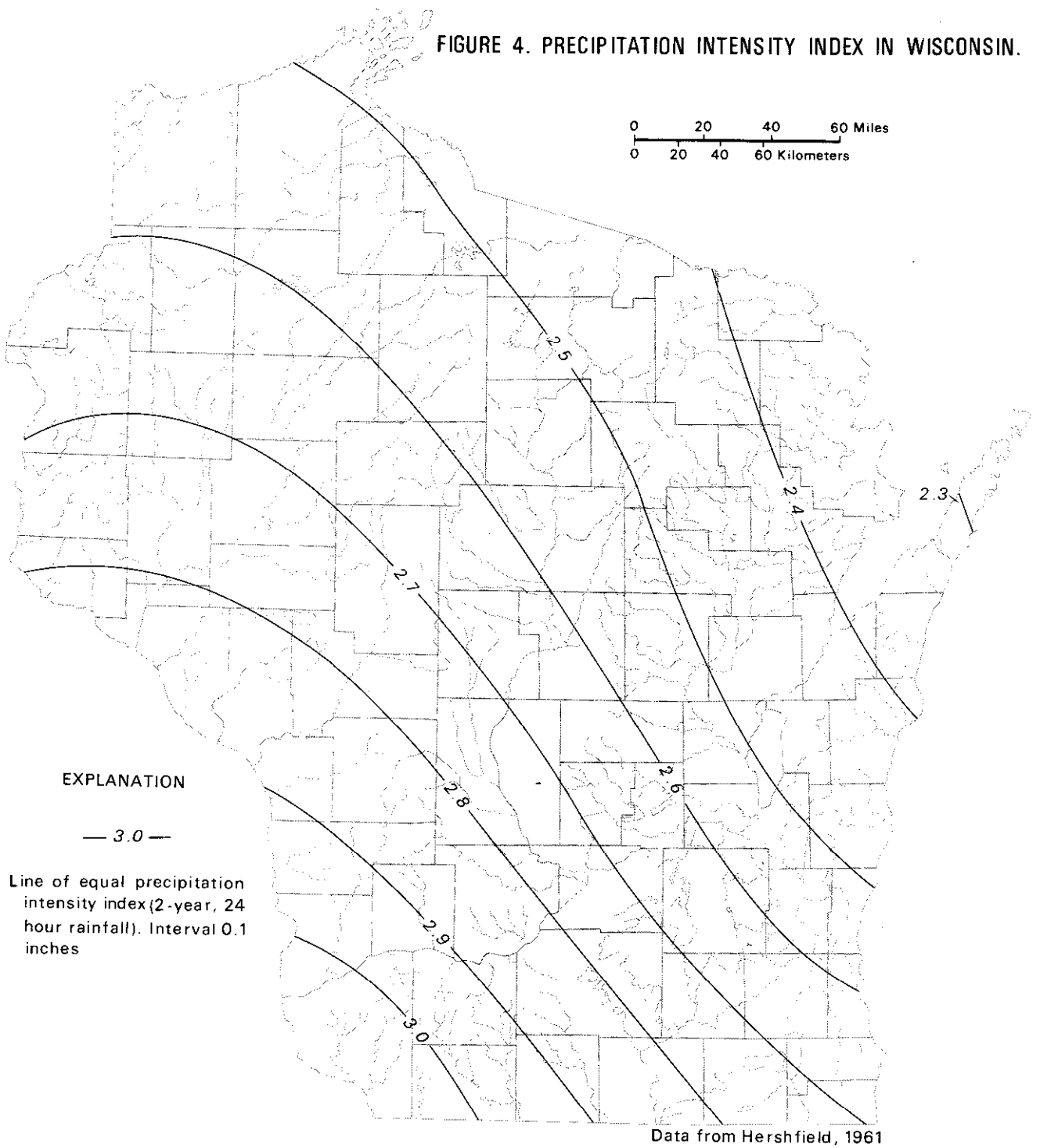
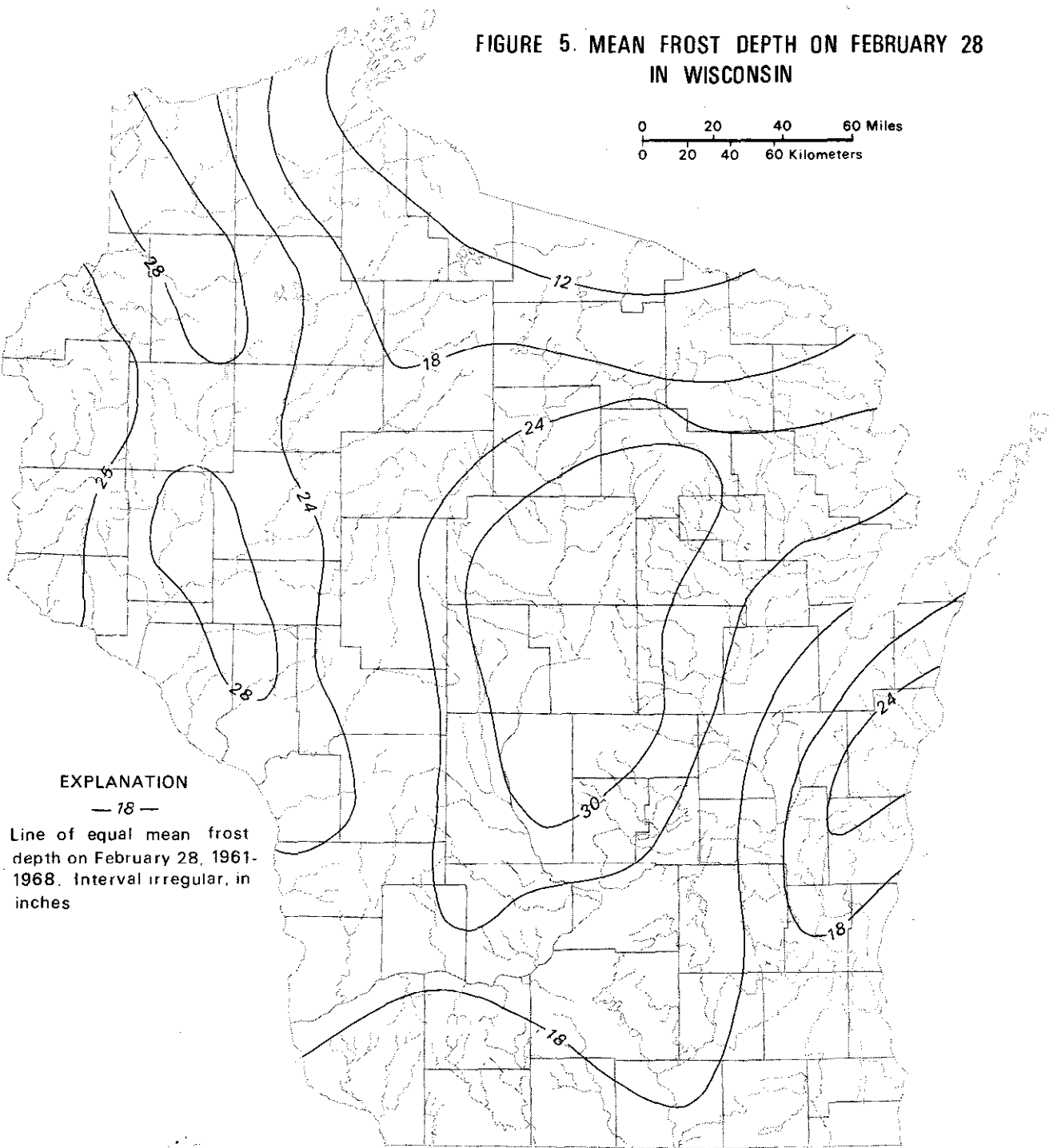


FIGURE 5. MEAN FROST DEPTH ON FEBRUARY 28
IN WISCONSIN

0 20 40 60 Miles
0 20 40 60 Kilometers



EXPLANATION

— 18 —

Line of equal mean frost
depth on February 28, 1961-
1968. Interval irregular, in
inches

Data from Wisconsin Statistical
Reporting Service, 1970

SOURCES AND SEDIMENT YIELD OF HAWAIIAN WATERSHED AND COASTAL SEDIMENTS¹

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ABSTRACT

The mineral composition as well as the texture of Hawaiian watershed and coastal sediments is dependent on various parameters. Geology, climatology, vegetation, stream slope and channel morphology, bathymetry, and cultural activities, are all important. Hawaiian streams enter the ocean basin through one of the following kinds of environment: estuaries, bays, lagoons, or mouths of tidal streams. The coastal environments serve as temporary sinks for tidal streams. The coastal environments serve as temporary sinks for the sediments. Four representative watershed coastal environments from Oahu were selected for detailed study. They were Kahana, Kaneohe Hawaii Kai, and Pearl Harbor.

INTRODUCTION

The mineral composition as well as the texture of Hawaiian watershed and coastal sediments is dependent on various parameters. Geology, climatology, vegetation, stream slope and channel morphology, bathymetry, and cultural activities are all important.

The geological setting of the Hawaiian islands is rather uniform. All six volcanic shields consist mainly of tholeiitic basalt with small amounts of alkalic basalt, nepheline basalt, trachyte mugerite, and hawaiiite. Coastal plain deposits consisting of terrestrial sediments and limestone are found on the older islands, such as Kauai and Oahu. The age of the island plays a major role in terms of the weathering products, for example, high gibbsite content in rocks from Kauai (older) as compared with low gibbsite content in rocks from Maui (younger).

Annual rainfall increases and becomes very frequent toward the mountain summits. The mean annual rainfall at Mount Waialeale on Kauai exceeds 450 inches. The annual rainfall along the windward side of the island chain is over 100 inches as compared with 20 inches along the leeward side. The entire chain is subject to heavy rainfall, on occasion reaching an intensity of several inches per hour. Runoff of the intense rain could account for the transporting of more than 90% of the fluvial sediment load (Jones et al., 1971).

¹Hawaii Institute of Geophysics Contribution No. 707.
Water Resources Research Center Contribution No. 76.

On the windward side of the islands, chemical weathering predominates over physical weathering. There the luxuriant vegetation covers roots and humus which protect the surface from erosion. The leeward side of the islands is in sharp contrast. There the slopes with little rainfall do not support a vegetation cover. Physical weathering is predominate over chemical weathering, but proceeds at a slower rate. The loose particles on the ground surface are subject to removal by raindrop impact and runoff.

Not a single stream flows into the ocean from Hilo to the southern boundary of Kohala Mountain on the island of Hawaii. The lava flows are too porous to sustain surface runoff. Surface runoff is not achieved until the lavas become partially sealed through chemical weathering or covered by volcanic ash (Macdonald and Abbott, 1970). Most of the watersheds are therefore located on the older islands. In general, the gradients of windward streams are steep as compared with the gentle gradients of the leeward streams.

Watersheds of Oahu

Hawaiian streams enter the ocean basin through one of the following kinds of environment: estuaries, bays, lagoons, or mouths of tidal streams. These environments serve as temporary sinks for the sediments of which Kaneohe Bay and Pearl Harbor of Oahu are two of the largest. Kahana Valley is chosen for this study because it represents the natural watershed (Fan, 1974). Maunalua Bay, located along one of the valleys (Hawaii Kai) rapidly being urbanized has seen excessive sediment accumulation within the last three years.

Kahana Bay

Kahana Bay (Figs. 1 and 2) located on the windward coast of Oahu (rainfall 75-240 inches/yr) is the drowned lower portion of Kahana Valley. The Kahana submarine canyon located at the opening of the bay is the seaward extension of Kahana stream (Coulbourn, 1971). The valley is covered with luxuriant vegetation; the stream enters the bay from a nearly unchanged valley, through a flat, swampy valley floor and a crescent-shaped calcareous beach. The Soil Survey Map (Foote et al., 1972) classifies the soils of the valley into seventeen series. Because of their similar mineralogical composition, four soil-mineral types were used in this study (Fig. 2). They were: (1) kaolinite and (2) Fe, Al oxides from the well-drained region; (3) minor amounts of montmorillonite from the poorly drained, flat, swampy valley floor; and (4) slightly weathered to unaltered rocks along the walls of the valley. The low sediment yield (Fig. 3) observed by Ekern (1975, personal communication) is probably due to the dense vegetation cover. Coulbourn (1971) noted that there are very small amounts of terrigenous materials in the bay (<20%), most of the sediments in the bay consisting of calcareous materials that derive from the fringing reef. The reddish plume that is present in the bay after storms is kaolinite-hematite derived from the soils of the valley.

Kaneohe Bay

Kaneohe Bay (Figs. 1 and 4) located on the windward coast of Oahu (rainfall >50 inches/yr) is a compound estuary-lagoon. Twelve streams drain into the bay. The watershed of the drainage area comprises about 32 square miles and contributes an estimated 37,000 tons of suspended sediment per year (Jones *et al.*, 1971). One of the largest (Kamooalii) streams carried a suspended sediment load of 9,470 ton/day during the 1969 flood (Fan, 1973). The average size consists distribution of the suspended loads consists of 50% clay, 42% silt, and 8% sand. The sediment yield is shown in Fig. 3. The following mineral suite has been identified in Kaneohe Bay and its drainage basin: calcite, aragonite, dolomite, magnesite, quartz, plagioclase, cristobalite, geothite, magnetite, maghemite, ilmenite, hematite, apatite, gibbsite, pyrite, anatase, mica, chlorite, talc, rutile, kaolinite, montmorillonite, nontronite and halloysite. Amorphous iron and silica are also present (Fan, 1974).

The Soil Survey Map (Foote *et al.*, 1972) classifies the soils of Kaneohe Bay drainage basin into twenty-two series. Because of their similar mineralogical composition, nine soil-mineral types were used in this study. They were: (1) kaolinite, (2) montmorillonite, (3) Al, (4) Fe oxides, (5) carbonate, (6) mixed (mixture of more than one soil-mineral suite), (7) poorly drained (mostly montmorillonite), (8) rock (slightly weathered to unaltered rock), (9) or fill (transported from various sources).

Twelve grab samples from Kaneohe Bay and a 1.5-meter core collected at the mouth of Kamooalii stream were analyzed for their clay mineral content. Reconnaissance X-ray diffraction studies indicate that the clay mineral distribution of the bay sediments is mostly kaolinite derived from the major soil-mineral type of the drainage basin. Up to 57% montmorillonite is recorded in south Kaneohe Bay. The montmorillonite is mainly derived from the soils of the southern shore of the bay. Raymundo (1965) reported that the Fe_2O_3 content of this soil ranges from 2.4% to 15.5%. This montmorillonite may possibly be nontronite. Small amounts of mica are present in the southern part of the bay. The mica possibly derives from the aeolian mica found at higher elevations of the Koolau Range. The broad and diffuse X-ray diffraction of the mica suggests authigenic origin.

Al and Fe oxides are commonly found in soils, usually occurring in the fine sand or silt fractions but not in the clay fraction. In times of storms, the reddish color of the bay water is due to Fe oxide coating on kaolinite. The rate of flocculation probably depends on the types of clay minerals, previous sorption levels, turbulence, and the concentration of sediments. The effect on Fe oxide weighting on kaolinite and flocculation behavior are not well understood.

Pearl Harbor

Pearl Harbor (Figs. 1 and 5), located in southern Oahu, is a true coastal plain estuary. Its three lochs (West, Middle, and East Loch) represent the drowned valleys of three major streams which joined to form a single river entering the sea and which now forms the main channel. Eight streams drain into Pearl Harbor (Fig. 6). Of the streams, only Honouliuli and Aiea are intermittent. Waikele stream and its tributaries Kippa and Waikakalaua carry 13,500 tons per square mile per year suspended sediments (Jones et al., 1971). They contribute to most of the sediments in Pearl Harbor. The unusual increase in sediment concentration in Kipapa stream between 1967 and 1974 observed by P. Ekern (1975, personal communication) is probably a result of the construction activities of developing Mililani Town. The high sediment yield of Waiawa stream (Fig. 3) compared with that of Waikele stream is probably a result of the urbanization along the lower portion of Waiawa stream.

Headwaters for the streams are in forest reserves in the high-rainfall area of the Koolau Range. Clay minerals are only present locally. Waikele stream and its tributaries pass through soils that consist mostly of kaolinite and Fe, Al oxides. Two types of montmorillonite are present in the Pearl Harbor area: one, occurring east of Pearl Harbor, derives from Salt Lake tuff; and the other, located north and east of Pearl Harbor, is, according to Hussain (1967), the product of transformation from metahalloysite. Montmorillonite content increases with depth, probably due to high pH and high base saturation in the subsurface. Montmorillonite is present in East Loch but not in Middle and West lochs. The sediments of the latter two are mostly derived from Waikele stream, in which kaolinite is the dominant clay mineral (Turner, 1975).

Hawaii Kai-Maunalua Bay

Long spurs of the Koolau Range slope gently from mountain crest to sea along southern Oahu except for a sudden break near sea level, the remnant of the sea cliff that formed when the sea stood about 25 feet above sea level approximately 38,000 years ago. This sea cliff remnant together with alluvium and colluvium deposits constitutes the present coastal plain (Fig. 6). Two subsequent eruptions along the Kaimuki and Koko rifts built a series of tuff cones (Diamond Head, Koko Crater) and brought Maunalua Bay into existence (Macdonald and Kyselka, 1967).

The area selected for study included four small watershed areas: Kaalakei, Hahaione, Kamilonui, and Kamiloiki valleys. Hawaii Kai Marina, formerly Kuapa Pond, drains into the eastern end of Maunalua Bay. Suspended sediments carried out from the marina during storms, and fine-grained sediments occurring in the pockets of Maunalua Bay, are resuspended, discoloring the bay.

The dominant clay mineral in the four valleys is montmorillonite. Kaolinite is present on the hilly slopes, and a mixture of both clays is found in the valley floors. The combination of low rainfall

(30 to 40 inches annually) and the poor drainage typical of the area is favorable for the formation of montmorillonite. Kaolinite is found where rainfall is higher and drainage is better. Kaolinite may also be transported onto the valley floor by erosional processes. Tuff along the western slopes of Koko Crater consists mostly of amorphous materials, some augite, zeolites, and calcite. These amorphous materials may be transformed into montmorillonite. Mud samples from Kuapa Pond and Maunalua Bay contain mostly montmorillonite; small amounts of kaolinite are also present (Sakoda, 1975).

SUMMARY

Four Oahu watersheds were selected to represent diverse environments:

Kahana Valley, natural watershed; Kaneohe Bay, drainage basin, typifying watershed-lagoon-bay complex; Hawaii Kai, urbanized watershed; and Pearl Harbor, agricultural-urban watershed-estuary complex. Kahana stream has the lowest sediment yield, compared with the stream in the urbanizing area, Kipapa Stream, has the high sediment yield.

ACKNOWLEDGMENTS

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FIGURES

1. Location of Oahu watersheds:
 (1) Kahana Valley; (2) Kaneohe Bay drainage basin;
 (3) Hawaii Kai; (4) Pearl Harbor drainage basin.
2. Soil-mineral map of Kahana Valley.
3. Sediment rating curves for Oahu streams.
4. Kaneohe Bay area showing location of streams.
5. Pearl Harbor drainage basin showing location of streams.
6. Soil-mineral map of Hawaii Kai area.

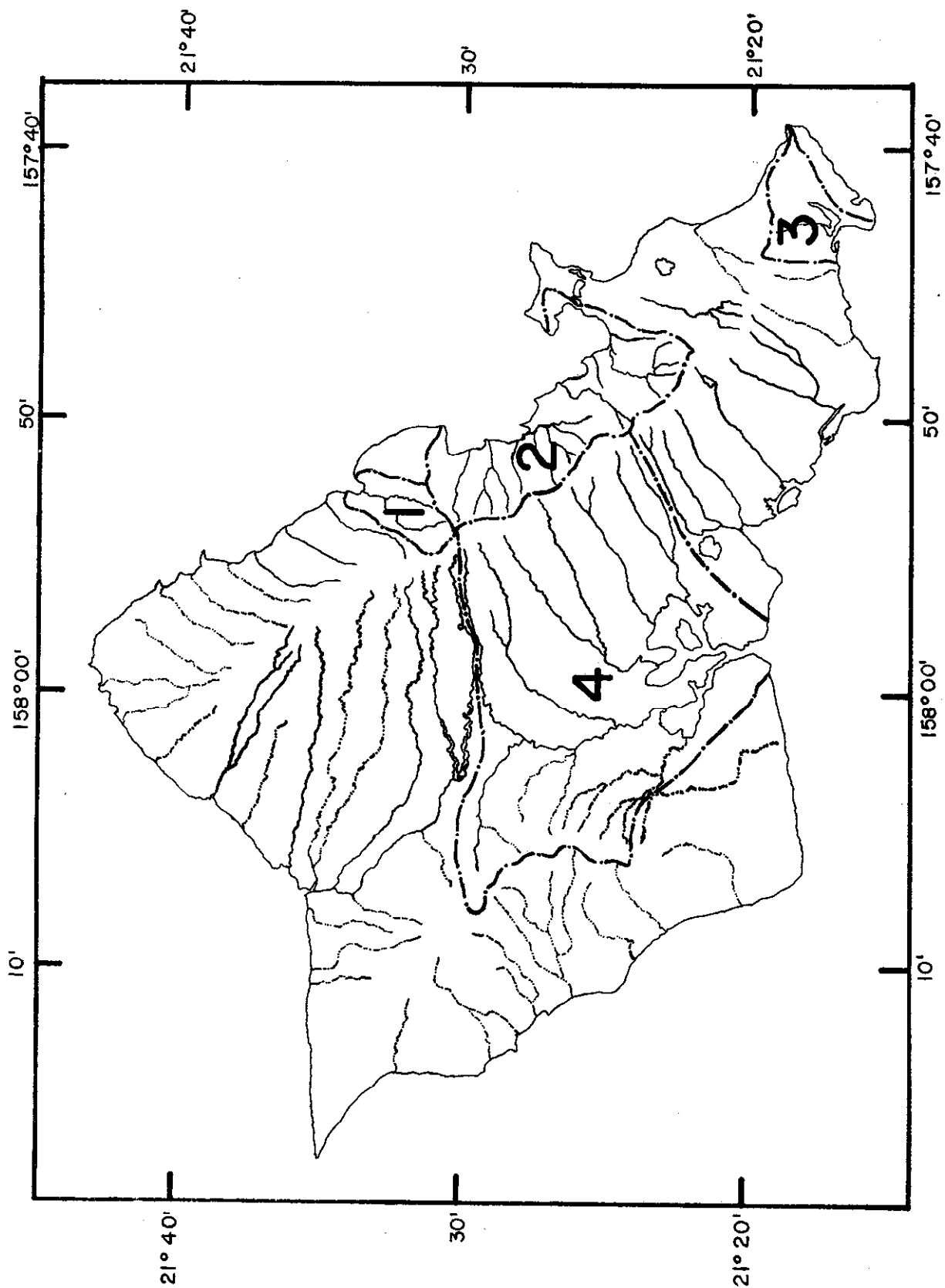


Figure 1.

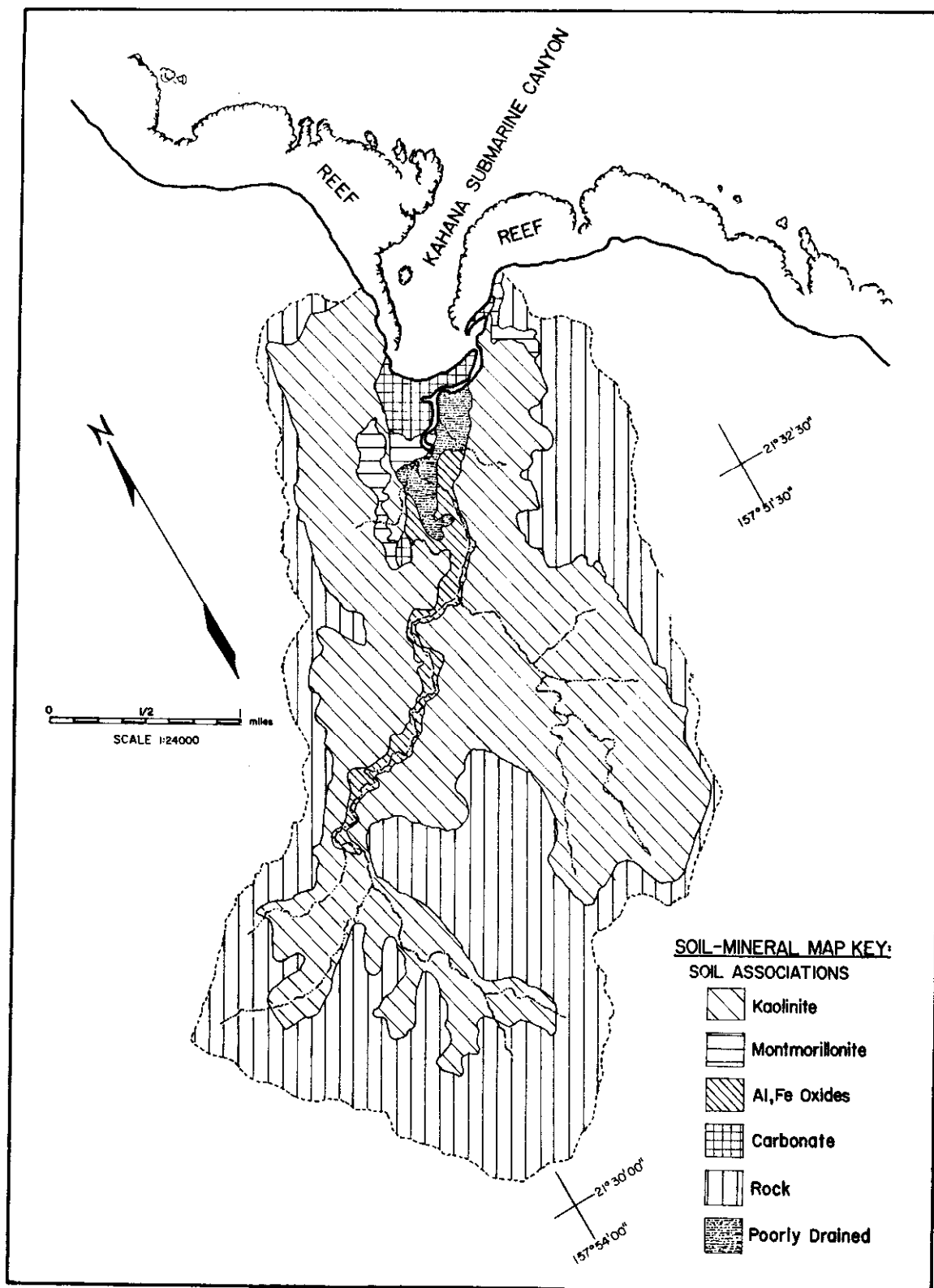


Figure 2.

SEDIMENT RATING CURVES FOR OAHU STREAMS

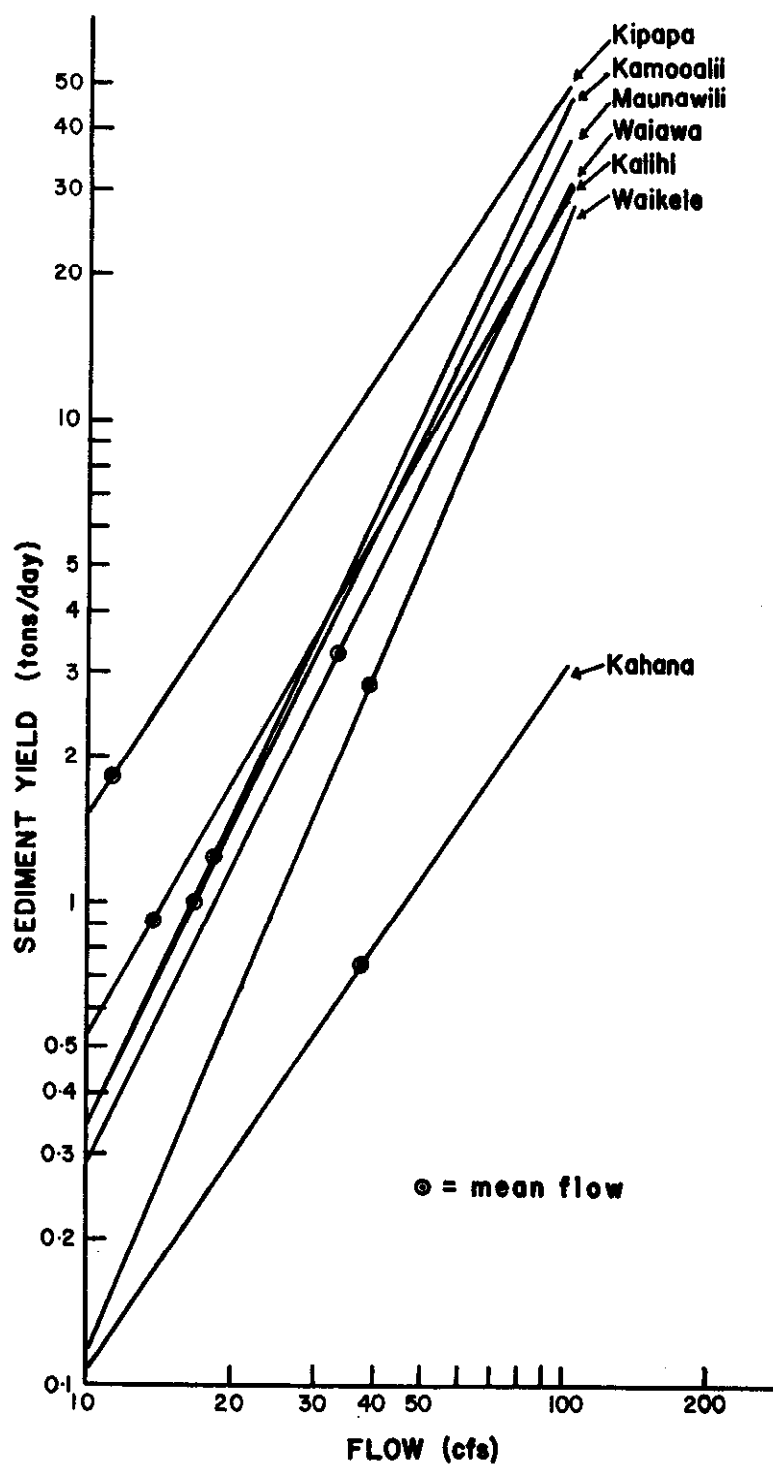


Figure 3.

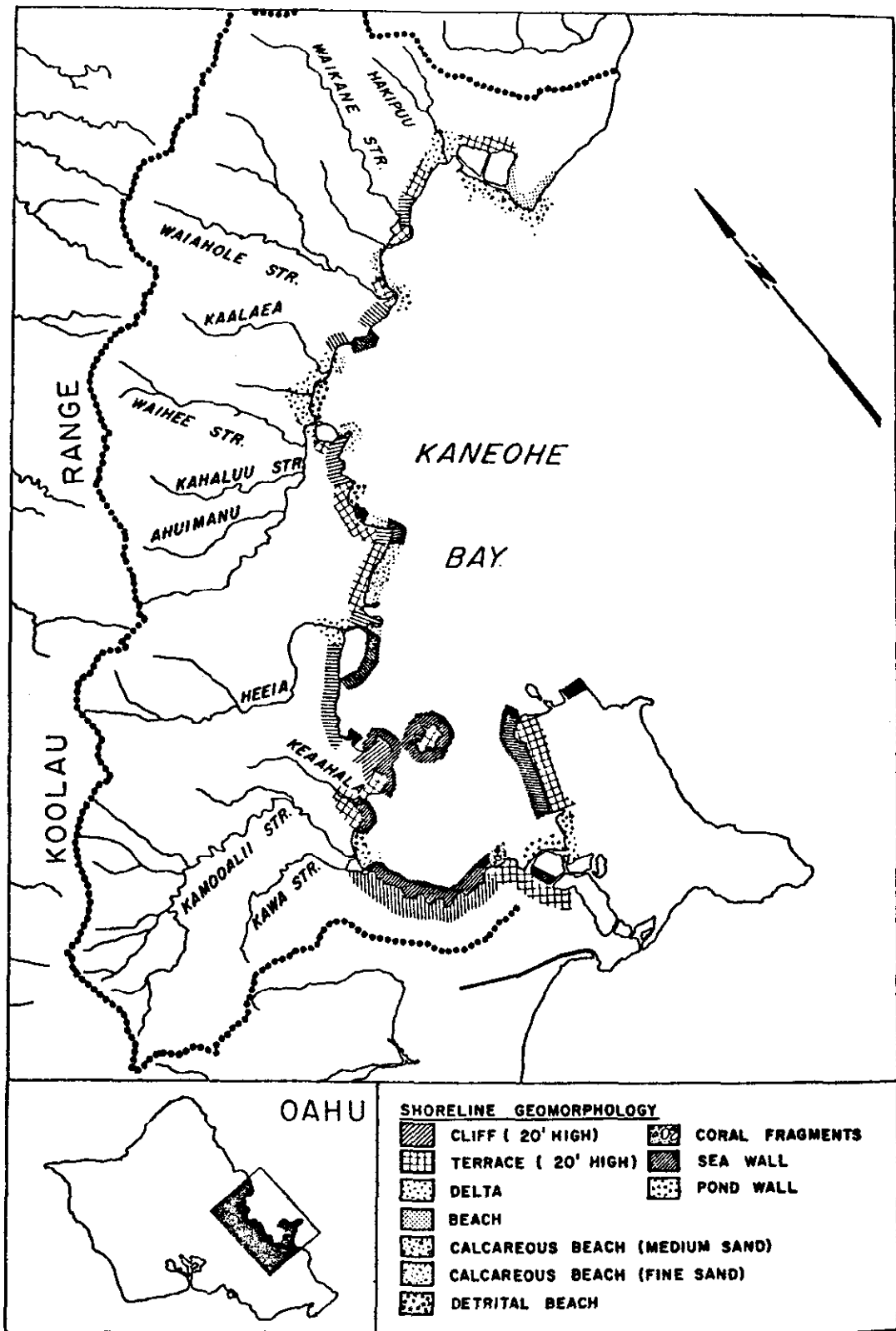


Figure 4.

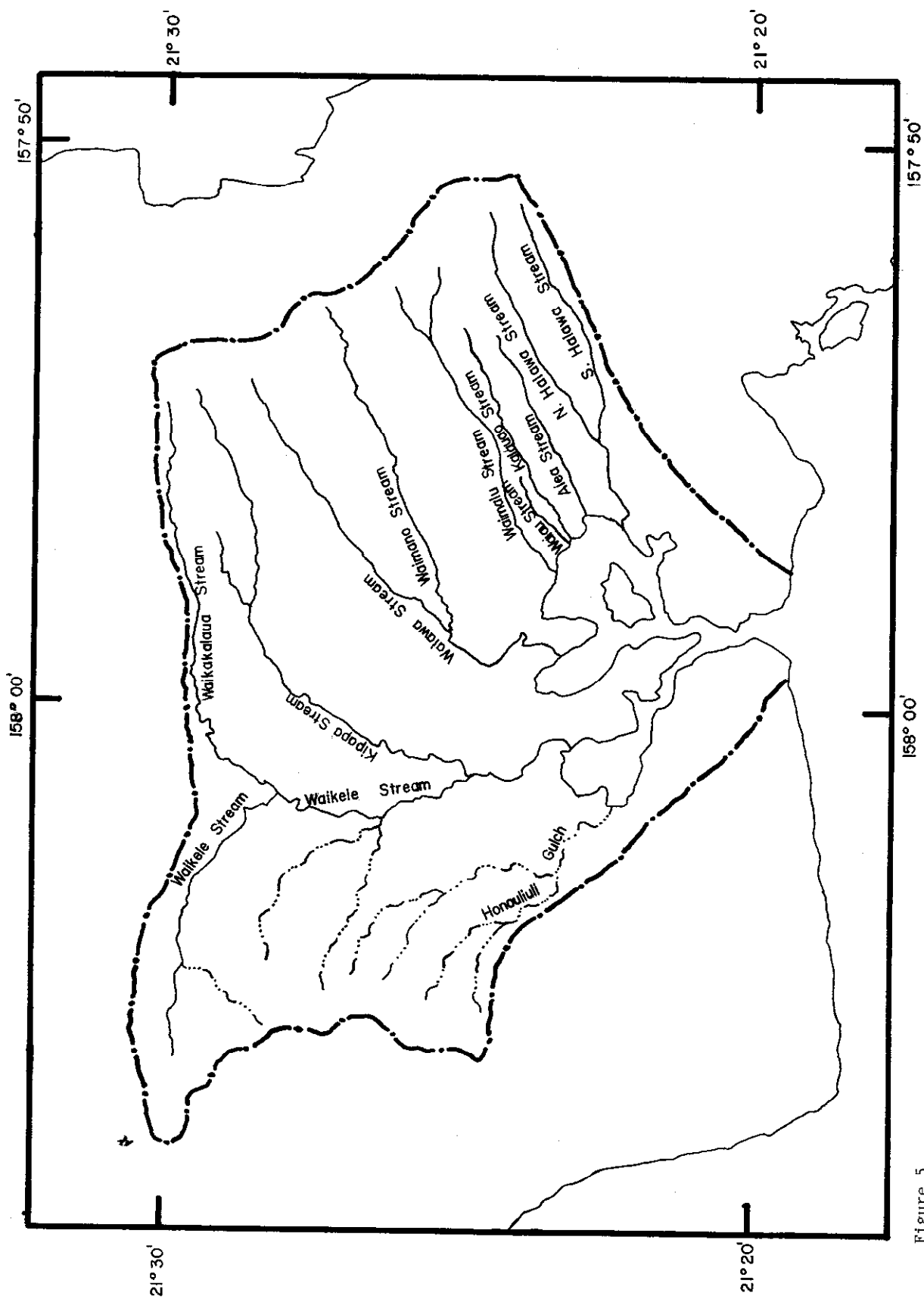


Figure 5.

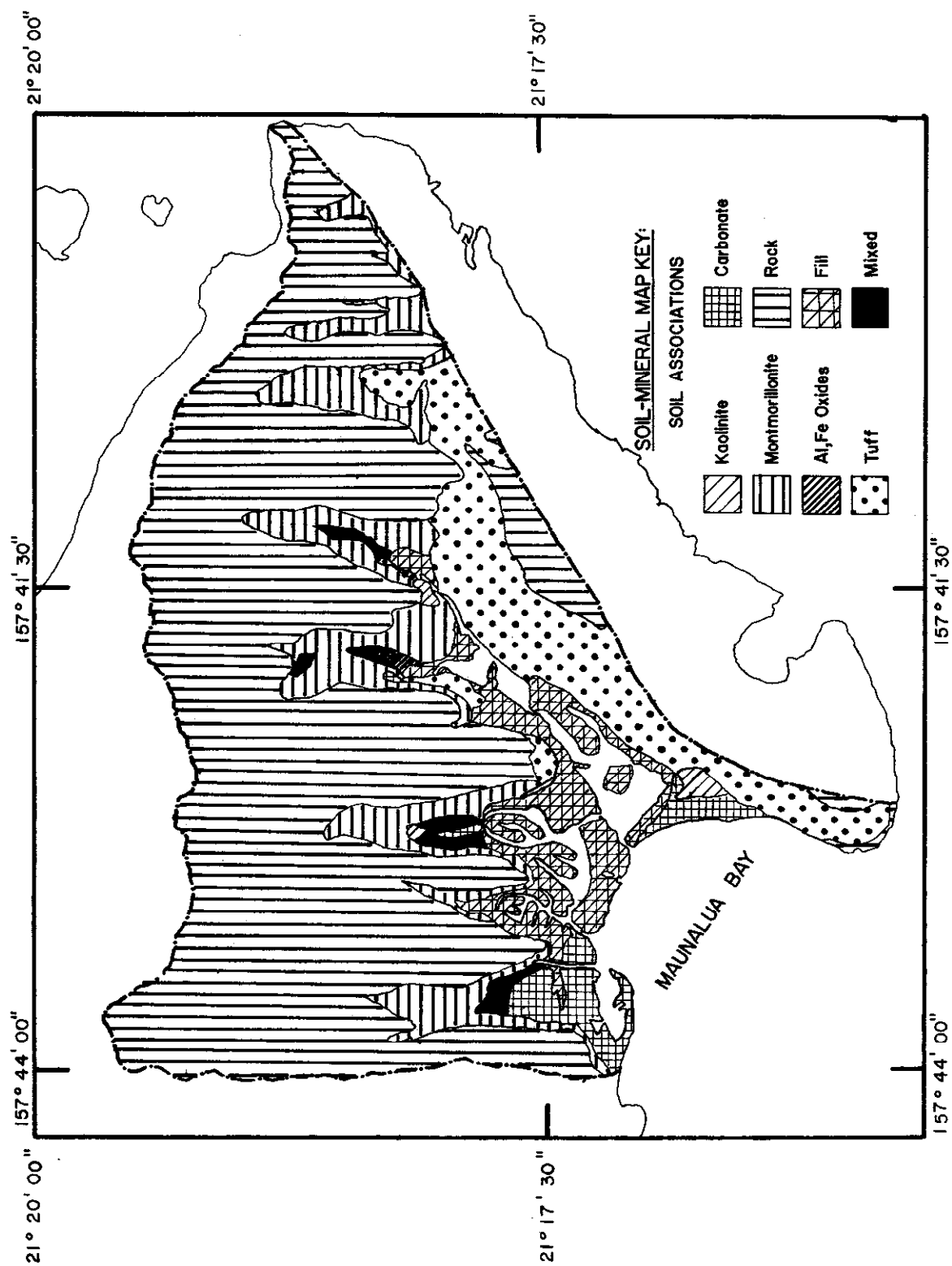


Figure 6.

The Hydrologic and Sediment Processes

in natural watershed areas.

by

G. Fleming^{*} and K.M. Leytham⁺

In a world rather belatedly concerned with rational use of its resources, the understanding, prediction and control of sediment processes is becoming a topic of some considerable importance. Sediment may effectively limit the useful life of storage facilities in some parts of the globe and in others sheet erosion and resulting soil degradation may be fatal to both human life and a nations viable existence. Unfortunately, the countries most afflicted by these problems are usually those least equipped to solve them. The onus must lie with the more advanced countries and various international agencies to develop approaches of universal applicability for land use management in the widest meaning of the word.

To provide methods of both universal applicability and increased accuracy, theorists have in the past decade been turning increasingly to the use of conceptual models in firstly simulating hydrologic processes and latterly in

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simulating the far more complex processes encountered in sediment problems. In modelling hydrologic processes, experience has shown that algorithms which incorporate parameters with physical meaning or directly measurable values are of considerable value. In this situation one does not necessarily have to rely on explicit calibration of parameters, from e.g. a historic streamflow record, to obtain satisfactory simulation results. Instead, one is in a position to estimate parameters from other data and yet still be confident that the results obtained from simulation will be relevant and reasonably accurate. The use of parameters with direct physical meaning is of even more importance in the practical application of conceptual sediment models. Even in the more advanced countries, sediment measurements of all kinds are sparse and the type of continuous sediment measurements required for anything but the most crude calibration, almost non-existent. The advantages of developing conceptual models with parameters based on easily measured values is quite apparent yet although this capability probably exists in theory, the almost complete absence of basic data is again a major barrier to further progress. Some work has been carried out for the E.P.A. by Hydrocomp International (1) in relating the parameters of the land phase of the Negev model (3) to physically measureable quantities and the pre-existing data base. This work, the continuation of a larger study (2), will be briefly outlined to demonstrate how parameters have been arrived at and to highlight the data requirements for using such conceptual models without explicit calibration. It is recognized that model calibration based on historic data

would be more desirable and more accurate but if conceptual models are to be used in practical applications in the near future their parameters should be tied to an existing data base or a data base which may be obtained easily within a short time period.

The algorithms developed by Negev for simulation of sheet erosion split the process into only two components:-

- i) production of soil fines by raindrop splash given per unit area for each time interval by:-

$$RER(t) = (1 - COVER(T)) * KRER * PR(t)^{JRER} \quad (1)$$

where:-

$RER(t)$ = soil fines produced during time interval t

$COVER(T)$ = percent vegetal cover as a function of the relative time within the growing season.

$KRER$ = coefficient of soil properties.

$PR(t)$ = precipitation during time interval t .

$JRER$ = exponent.

- ii) pick up and transport of soil fines by overland flow, given per unit area for each time interval by:-

$$SER(t) = KSER * SRER(t-1) * ROSB(t)^{JSER} \quad (2)$$

where:-

$SER(t)$ = fines pick-up during time interval t

$KSER$ = coefficient of pick up

ROSB(t) = overland flow occurring during time interval t.

SRER(t-1) = reservoir of deposited fines existing at the beginning of time interval t.

JSER = exponent

The soil fines produced by raindrop impact are immediately available for pick up and transport by overland flow if such flow is occurring. If such flow is not taking place, the soil fines are accumulated in a reservoir of fines available for transport by overland flow in some future time period. Occurrence of overland flow in any rainfall event was predicted in the model by using certain components of the HSP hydrologic simulation program (4). An important aspect of this simple model is that sheet erosion is limited by the quantity of available detached fines. Earlier methods had a drawback in that it was assumed that sediment was transported at a potential rate whether or not detached material was actually available for transport.

The development of the Negev model has in the first instance been restricted to the U.S.A. The most important source of readily available data on erosion processes in the U.S.A. is that presented for the Universal Soil Loss Equation (5), and, in the absence of other data sources, this information was used extensively in developing the present parameter estimates. As will be recalled the U.S.L.E. is of the form:-

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (3)$$

where:-

A = soil loss, tons/acre

R = rainfall factor; the number of erosion index units in a specified time interval.

K = soil erodibility factor, tons/acre per unit of erosion index R

L = slope - length factor

S = slope - gradient factor

C = cropping - management factor

P = erosion - control practise factor

Of these parameters R, K and C are primarily concerned with soil detachment or production of fines, whereas L, S and P primarily effect soil transport.

The precipitation term $PR(t)^{JRER}$ in Negev's algorithms (equation (1)) may be regarded as a rainfall erosion index similar to R of the U.S.L.E.. By making Negev's term directly equivalent to R, use may then be made of the U.S.L.E.'s soil erodibility factors. In the U.S.L.E., for a specific storm:-

$$R = \frac{E I_{30}}{100} \quad (4)$$

where:-

E = total energy input during a storm event

I_{30} = maximum thirty minute rainfall intensity, in/hr.

The immediate problem was to express $E I_{30} / 100$ in terms of

$PR(t)^{JRER}$ Wischmeier and Smith (6) give rainfall energy:-

$$E = 916 + 331 \log_{10} I \text{ foot-tons per acre inch} \quad (5)$$

for $0.01 \leq I \leq 6$ in/hr

In the range $0.05 \leq I \leq 1$ in/hr this may be approximated by:-

$$E = 880 I^{0.14} \text{ foot-tons per acre inch.}$$

Rainfall depth in T minutes is $\frac{T}{60} \cdot I$ inches. Hence total energy input in T minutes is:-

$$E = 880 \frac{T}{60} \cdot I^{1.14} \text{ foot-tons per acre} \quad (7)$$

$$\therefore R = \frac{E}{100} \cdot \frac{I_{30}}{I} \approx 8.8 \cdot \frac{T}{60} \cdot I^{2.14} \quad (8)$$

If the modelling interval T were 60 months then,

$$R = 8.8 PR(t)^{2.14}$$

which is the form of relationship used by Negev. To permit modelling at various time intervals the more general expression (8) above was used in an amended version of Negev's model.

Now, if, as a first approximation, one neglects the soil compaction process, in the long term total soil loss from an area would be equal to the total amount of soil detached since the storage effects becomes negligible. Hence, as the same rainfall erosion index is being used, the soil erodibility

factor:-

$$KRER = K$$

Nomographs for assessing K are presented by Wischmeier, Johnstone and Cross (7). The information used in the nomographs is:-

- (i) Percentage silt + very fine sand
- (ii) Percentage sand
- (iii) Percentage organic matter
- (iv) Soil Structure)
- (v) Permeability) qualitative values.

This is normally easily obtained from soil maps or simple field measurements.

The term COVER(T) in equation (1) represents the protection offered to the soil by such factors as vegetal cover, mulch, ground litter etc.. The cover will be dependent on such factors as crop type, management practices (e.g. whether residues are left on fields or removed), row spacing, crop condition and so on. Unfortunately virtually no data seems to be readily available concerning quantitative values of cover. As sediment production seems to be quite sensitive to cover this is a serious shortfall in the present data-base. Some estimated cover data has recently been presented by Wischmeier (8) and cover was roughly estimated from the U.S.L.E.'s cropping-management factor, c, in the course of work on the PTR model (1). However, there is a distinct

lack of data relating co_{er} to stage of growth, crop condition and management practices.

To summarize the soil detachment algorithm, we now have:-

$$RER(t) = (1 - COVER(t)) * K * 8.8 * \frac{T}{60} * I(t)^{2.14} \quad (9)$$

which may be written:-

$$\underline{RER(t) = (1 - COVER(t)) * KRER * I(t)^{JRER} \text{ tons/acre.}} \quad (10)$$

where:-

$$KRER = 8.8 * \frac{T}{60} * K$$

T = time step, minutes

$$JRER = 2.14$$

Fines transport is given by:-

$$SER(t) = KSER * SRER(t-1) * ROSB(t)^{JSER}$$

The above form of this algorithm implies that soil transport per unit area is a continuous linear function of the total quantity of detached fines on the whole of the area being modelled. This is considered to be conceptually incorrect. A better approach would be to use an expression of the form:-

$$SER(t) = KSER * f(SRER(t-1)) * ROSB(t)^{JSER}$$

where $f(SRER(t-1))$ could be kernel function used to represent the areal variability of detached fines. The general shape of such a function is shown in Figure 1. For the present however the following term was assumed:-

$$SER(t) = KSER * ROSB(t)^{JSER} \quad (11)$$

subject to:-

$$SER(t) \leq \frac{SRER(t-1)}{AREA} + RER(t)$$

i.e. fines pick-up cannot exceed the quantity of fines made available by detachment but is otherwise independent of $SRER$.

The best way of simulation wash-off without explicit calibration is perhaps to directly use a sediment transport equation. Foster and Meyer (9) reviewed various sediment transport equation and concluded that in theory Yalin's bedload formula (10) was the one most likely to represent sediment transport by shallow flow. However, there are several objections to the use of Yalin's formula (e.g. the depth of flow should be much greater than the particle size) and a method developed specifically for shallow flow transport could be of great value. To adhere to the form of algorithm put forward by Negev, it was assumed that:-

$$SER(t) = CONSTANT * n^k * L^l * S^m * d_{50}^n * ROSB^P \quad (12)$$

where:-

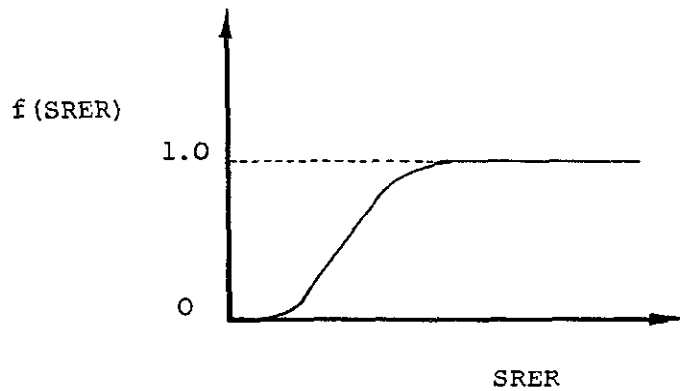


Figure 1. General Function Used to Represent Areal Variability of Detached Fines.

n = Mannings roughness for overland flow

L = slope length, ft.

s = overland flow gradient

d_{50} = particle diameter, ft.

$ROSB$ = overland flow rate, in/hr.

$k, l, m, n, p,$ = exponents.

Using Yalin's formula, SER was found for the range of values of $n, l, s, d_{50}, ROSB$ thought most likely to occur in practise and multiple regression then used to obtain the exponents in equation (11). The result gave:-

$$SER(t) = (14900 * n^{1.95} * L^{0.81} * s^{1.84} * d_{50}^{0.13}) * ROSB^{1.89} \text{ U.S. tons/acre/hr.}$$

Hence in equation (11)

$$KSER = 14900 * n^{1.95} * L^{0.81} * d_{50}^{0.13}$$

$$JSER = 1.89$$

obviously it would have been better to use Yalin's formula directly for simulating wash-off and in the detachment algorithm the full expression of rainfall energy, equation (5), could have been used in place of equation (6). The aim here was simply to suggest how one particular conceptual model could be adjusted for its parameters to be obtained from an existing data base or from easily measured values. The parameters obtained should provide for reasonable simulation for sheet erosion in the U.S.A. within the confines of the simple conceptualisation inherent in Negev's model. Other models, such as that under development by Fleming and Fahmy, (11,12,13) consider the processes involved in sheet erosion in much greater detail, accounting for such factors as armouring, soil compaction, detachment by both rainfall and runoff, rill and gully processes and so on. However, the application of this type of model will be restricted by the lack of adequate data. Research work continues on these models to test the importance of various algorithms and to consider the physical implications of parameter values. Even with the present simple model parameter estimation within the U.S.A. would encounter some problems because of lack of data and its use outside the U.S.A. is subject to many uncertainties because parameter estimation have been based heavily on U.S. data i.e. the U.S.L.E.. For use of

this simplistic approach within the U.S.A. the following extensions to the present data base would be required:-

- i) extensive investigation of values of ground cover given by crops, mulch or residues in various conditions or various growth stages.
- ii) investigation of values of Manning's roughness for overland flow through various croplands again under a variety of management conditions.
- iii) a study of the effects of erosion-control practises and how they may be incorporated in parameter values.

For world-wide use the problems are far greater but to the above three conditions could be added:-

- iv) some measurements of rainfall energy to study deviations from equation(5).
- v) Establishment of plots to establish the relationship between physical characteristics such as soil type, vegetation cover etc and the detachment-transportation process for the region being studied.

Also, as stated earlier, within the confines of Negev's model, improvement's could be made to the wash-off algorithm by developing a sediment transport formula specifically for the shallow flow condition.

The parameter estimation methods outlined above still remain to be tested so at this stage no claim may be made about their true validity. However, the study certainly highlights the type of basic data which would need to be

assembled for practical applications of land surface erosion models.

Conclusions

The widespread practical application of conceptual sediment models would appear to be limited by serious shortages of basic data. This is true even for simple models such as Negev's, although it is hoped that sufficient data may be obtainable for its use to be viable within the U.S.A., as outlined in this paper. One problem is perhaps the fact that in this multi-disciplinary subject data sources are widely scattered often in obscure places. The establishment of some control archive for data concerned with land-use activities and management could be of considerable value.

Another problem which has been recognized in the past is the chaotic state of sediment transport study with its enormous variety of definitions and terms, units, methods of measurement and a very confusing array of formula and equations which often do not explicitly state assumptions of limits of applicability. Again it is hoped that this conference may provide some impetus to the rationalization of work in this field.

Critical land-use problems in wide areas of the U.S.A. and Africa have recently publicized the effects of soil degradation and soil erosion. In the immediate future simple conceptual models could be of value as basic planning tools or perhaps avoid the types of problem encountered in the past. However, once again lack of basic data could severely limit the practical value of their use.

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